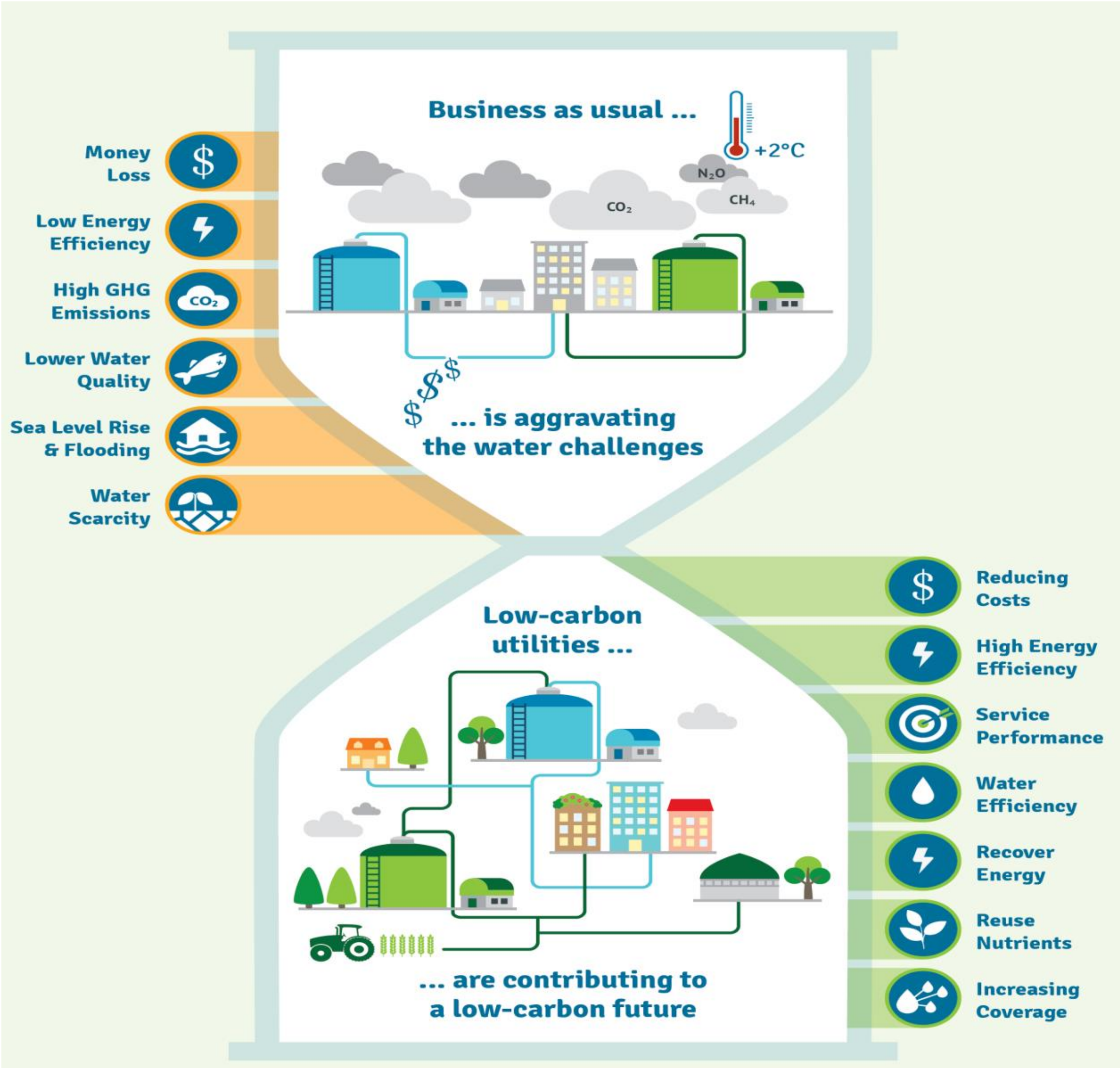
Towards a climate-neutral wastewater treatment plant in Leeuwarden



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Abstract

The research aims to analyze the current conditions of Leeuwarden wastewater treatment plant (WWTP) in the Netherlands, WetterSkip Fryslan (WF) which targets to be climate neutral by 2030. However, the current high energy consumption and greenhouse gas (GHG) emissions in the WWTP are considerable and analysis is required to examine the potential of climate neutrality. Therefore, this thesis focuses more on 1) the current technological state of the art of the WWTP with the relative energy inputs and outputs 2) the identification, classification and calculation of the GHG emissions associated with the plant and finally 3) the changes that are required to reach climate neutrality.

To achieve the research goals, a literature review was carried out to provide insights into the energy production and consumption in WWTP, the treatment technologies used, the emission factors for each source of emitted process and finally the technologies which can provide climate neutrality or even more preferable climate negativity. Secondly, preliminary research includes primary and secondary data which are gathered and examined. The primary data of this research are derived from personal communications with members of the water board WF. The secondary data results from the water board documents, related to the energy sources, energy consumption, energy generation, current greenhouse gas emissions, the used technologies, its energy policy and climate agenda and documents from the national and provincial level in the field of energy regulations and environmental policies.

Abstract

Het onderzoek heeft tot doel de huidige omstandigheden te analyseren van afvalwaterzuiveringsinstallatie Leeuwarden (RWZI) in Nederland, WetterSkip Fryslan (WF), streeft ernaar om in 2030 klimaatneutraal te zijn. Het huidige hoge energieverbruik en de uitstoot van broeikasgassen (BKG) in de RWZI zijn echter aanzienlijk en er is een analyse nodig om de mogelijkheden van klimaatneutraliteit te onderzoeken. Dit scriptie richt zich dan ook meer op 1) de huidige stand van de techniek van de RWZI met de relatieve energie input en output 2) de identificatie, classificatie en berekening van de BKG-uitstoot van de installatie en tenslotte 3) de veranderingen die nodig zijn om klimaatneutraliteit te bereiken.

Om de onderzoeksdoelstellingen te bereiken werd ten eerste een literatuurstudie uitgevoerd om inzicht te krijgen in de energieproductie en consumptie in RWZI, de gebruikte zuiveringstechnologieën, de emissiefactoren voor elke bron van geëmitteerde processen en ten slotte de technologieën die klimaatneutraliteit of zelfs nog meer de voorkeur geven aan klimaatneutraliteit kunnen bieden. Ten tweede omvat het vooronderzoek primaire en secundaire gegevens die worden verzameld en onderzocht. De primaire gegevens van dit onderzoek zijn afgeleid van persoonlijke communicatie met leden van het waterschap WF. De secundaire gegevens vloeien voort uit de waterschapsdocumenten, die betrekking hebben op de energiebronnen, het energieverbruik, de energieopwekking, de huidige broeikasgasemissies, de gebruikte technologieën, het energiebeleid en de klimaatagenda van het waterschap en documenten van het nationale en provinciale niveau op het gebied van energieregelgeving en milieubeleid.

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List of acronyms

AKA: Microbial electrochemical snorkel with short-circuited microbial cell
AR5: Fifth Assessment Report
BEAMR: Bio Electrochemically assisted microbial reactor
BMS: Behavioral, Management and Social Sciences
BOD: Biological oxygen demand
CCS: Carbon capture and storage
CDM: Clean Development Mechanism
CER: Certified Emissions Reduction Credits
CH_4: Methane
CHP: Combined heat and power
CO_2: Carbon Dioxide
COD: Chemical oxygen demand
FO: Forward Osmosis
GWP: Global Warming Potential
IPB: Integrated photo bioelectrochemical system
MECC: Microbial electrolytic carbon capture
N_2O: Nitrous oxide
NET: Negative emissions technology
NL: The Netherlands
PE: Population equivalent
PF/MFC: Plug flow microbial fuel cell
RVO: Rijksdienst Voor Ondernemend Nederland
RO: Reverse Osmosis
SNB: Slibverwerking Noord-Brabant
WF: Wetterskip Fryslan
WWTP: Wastewater treatment plant

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Throughout the writing of this thesis, I have received significant support and assistance. Therefore, I would like to thank my supervisors, Dr Maarten Arentsen, Dr Luewton Agostinho and Mr Arjan van den Hoogen whose expertise and contribution was significant in the formulation of the research topic and the structure of the thesis in particular. Further, I am grateful to Wetterskip Fryslan allowing me to work on this interesting thesis topic which highly contributed to my personal growth.

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Chapter 1 Introduction

1.1 Background

Wetterskip Fryslân (WF), which is the organization behind the case study of this thesis and the provincial water board of Fryslân, aims to reach energy neutrality by 2025, by using sustainable energy. Further, it aims to be a climate-neutral water board by 2030, by eliminating greenhouse gas (GHG) emissions to zero. Although the organization operates 27 wastewater treatment plants (WWTP) the analysis is focused on the WWTP in Leeuwarden. The aim of this thesis is the identification of the total GHG emissions of the WWTP to propose possible intervention solutions for the reduction and/or elimination of its GHG emissions and thus, to reach climate-neutral conditions. Here it is essential to clarify that although the case study is based on the WWTP in Leeuwarden, the identification of the GHG emissions and the analysis of possible solutions for their elimination, tackle the broader problem of the wastewater treatment processes in the Netherlands.

In addition to the indirect emissions that are derived mostly from the energy use, direct GHGs, methane (CH_4), nitrous oxide (N_2O) and biogenic carbon dioxide (CO_2) are emitted during the wastewater treatment processes. According to Lu et al., (2018) moving towards climate neutrality by improving the energy balance of the WWTP is an issue of great attention at this moment. It is noticeable that great improvement has been reached to maximize energy efficiency and to recover renewable energy from the wastewater by using traditional wastewater treatment technologies such as activated sludge and anaerobic digestion. However, not much has been done regarding reducing the emission in these sites. This is directed by several European and national policies and initiatives, in conjunction with the European Union's 2030 Climate and Energy Policy Framework which requires a 40% reduction in GHG emissions by 2030 related to 1990 baseline (DECC, 2015). Furthermore, under the Dutch Climate Agreement published by the Ministry of Economic Affairs on the 28th of June 2019, there is a significant direction towards a low carbon future, where companies, including those in the water sector, have to reduce their CO_2 emissions 49% by 2030 and 95% by 2050. To achieve this goal, there is growing research into the maximization of energy recovery and increased methane production by using alternative technological approaches (Sweetapple et al., 2014).

However, the approaches mentioned above can be considered as adaptive measures for global warming. These adaptive measures can only reduce fossil fuel consumption and its associated carbon emissions (Indirect GHG emissions), whereas few have looked at the additional possibility of using wastewater and the organics included as a valuable source for products and fuels. Regarding the quantity of wastewater produced annually and its positive relation with population, there is great potential for contribution from the wastewater treatment to meet the Paris agreement, national and organizational goals.

Water authorities cannot consider wastewater as a by-product which has to be treated and processed, but as a source for energy, raw materials and clean water (https://www.efgf.nl/english/, 2018). Therefore, the 21 Dutch Water Authorities, including WF, the umbrella organization of the water authorities in the Netherlands, Unie van Waterschappen, the Foundation for Applied Water Research (STOWA), the Green Gas Foundation, The Netherlands Nutrient Platform and many other research institutions have already joined forces in order to reach a more sustainable growth of the water industry and the national goals, taking into account that the focus has been changed due to the high energy demand but also the high amounts of released direct, indirect and biogenic emissions during the treatment processes on WWTPs.

Although carbon neutral WWTPs have been described (SUEZ Environment, 2012; USEPA 2014), there is no global general agreement of what should be covered under the term ‘carbon’ regarding carbon reduction and carbon footprint. Vourdoumpas (2018) for example, analyzed the potential of zero carbon emissions in a WWTP in Crete by including the indirect CO_2 emissions associated with the energy use and providing solutions regarding mostly the energy efficiency. This strategy is in line with the carbon reduction commitment but not in the same line with the needs described by the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The AR5 Report in 2014, stated the need for drastic actions for the removal of CO_2 from the atmosphere by negative emissions solutions (NETs) and other techniques as described further, which also can occur within existing wastewater infrastructure (Fuss, 2017; Minx et al., 2017;

IPCC, 2014). This means that in the future, NETs and other solutions discussed, may transform the carbon-emitting WWTP into circular water resource recovery units which converts these resources into energy, nutrients, water and valuable carbon products with financial, environmental but also social benefits (Lu, 2018).

Therefore, it can be said that an area for research is created regarding the elimination of GHG at the WWTPs since the reduction of energy use and its efficiency are not enough and may prove fruitless if the goal is to mitigate global warming (Sweetapple, 2015). Further, based on the analysis of biogenic emissions in chapter 3, it can be said that further evaluation of those has to be conducted on a global scale (Europa.eu, 2018). Currently, there is no empirical example in the Netherlands of a climate-neutral WWTP and the systems of NETs and other innovative biological, physical and chemical treatment methods are still in the embryonic stage. As a result, there is limited maturity and expertise of climate-neutral systems in combination with sustainable energy production and supply in The Netherlands. This research can thus contribute to enhancing the knowledge by gathering and analyzing information from scientific literature, empirical documentation and experiences with this concept.

1.2 Definition climate neutrality

Based on the performed literature review, a precise definition of Climate Neutrality is still controversial. Under the Kyoto Protocol, Paris Agreement, COP21 and other definitions (Levin et al., 2015), it seems that Climate Neutrality can be reached if CO_2 and other greenhouse gases are decreased to a minimum and the remaining are offset with carbon sequestration. However, this definition is not precise since this minimum level is not quantitatively defined. Under the Clean Development Mechanism (CDM) of the Kyoto Protocol, an organization has to participate in projects of saleable certified emission reduction credits (CER) equivalent to tones of CO_2, which can be contributing to the Kyoto targets. By definition of COP21, climate neutrality means that every ton of anthropogenic GHG released is compensated with an equivalent amount of CO_2 removed. However, this term does not represent the need for mitigation concerning global warming, since it was found that 500-1200 Gt CO_2 eq is associated with 2015 and no space for postponing action is further left (Fuss, 2017). Therefore, in this thesis, 'climate neutrality' will be defined as the annual zero net anthropogenic GHG emissions without including the possibility of compensation by offsetting. This definition means that although energy neutrality cannot be in a different line of climate neutrality strategies and implementations, it will not be incorporated into this research. Therefore, the suggestion of energy efficiency and balance solutions are excluded from this thesis. This means the focus of this work will be on the identification and calculation of the total GHG emissions associated with the plant and some discussion about possible solutions. Lastly, it is important to stress that factors such as investments, financial costs, maintenance, and detailed CO_2 reduction were excluded from this study. It is, nevertheless, recommended to include these factors in future studies.

1.3 Research Objective and research questions

The main aim of this thesis is to explore the aspects of climate neutrality which are proposed in the energy policy and climate agenda plan of WF and to make a comprehensive analysis of the current situation of the WWTP in Leeuwarden. This analysis includes the current technological state of the art, the energy, water stream and resources used, inputs- outputs, flow scheme of the WWTP as well as GHG emissions analysis by presenting the related carbon footprint of the WWTP. Here it is important to mention that the calculation of the GHG emissions associated with the plant was made in a theoretical level. This means that measurements of actual GHG emissions on-site are excluded from this thesis due to the time limit. Finally, some intervention solutions are provided by highlighting the technological options of capturing carbon (mitigating measures) instead of using biological treatments for carbon degradation. Based on this introduction and the research objective, the research question has been formulated as follows:

"What is climate-neutral wastewater treatments and what are technologically feasible options to achieve climate neutrality in the wastewater treatment plant in Leeuwarden?"

1.4 Sub-questions

In order to answer the main research question, the following sub-questions will be answered:

1. What is the current technological state of the art of the WWTP Leeuwarden?
2. What is the current emission of GHG in the WWTP in Leeuwarden?
3. What technological options are feasible for climate neutrality in the WWTP?

1.5 Research Methodology

The table below describes the different research strategies and the data sources used, based on the research stages of this study. An elaborated analysis of the research methodology is provided beneath.

Table 1. Research Strategy

Research Stage	Research Strategy	Data sources
Exploration	-Desk Research	- Scientific literature - Official documentation
Understanding & analyzing	-Desk Research -Interviews -Energy and GHG mass balances of current processes	- Field experts - Scientific literature - Official documentation
Designing	-Desk Research -Interviews -Workshop with experts	- Field experts - Official documentation - Scientific literature
Evaluation	-Conclusions, Recommendations	- Based on findings

The research methodology of this study consists of a theoretical conceptual model extracted from the existing literature. According to Gonzalez and Sol (2012), there are 4 stages which define the research methodology, and these are: 1) Exploration, 2)

Understanding and Analyzing, 3) Designing and 4) Evaluation. Through the research methodology, insights into the conditions of a climate-neutral WWTP are provided.

1) **Exploration**: The aim of this stage is to explore the theoretical key conception of the research, climate neutrality in the WWTP, by researching scientific literature and official documents. The research strategies of this stage are desk research related to available wastewater treatment technologies, the energy production and consumption of WWTPs and the responsibilities of the water boards in The Netherlands. Consequently, the role and position of the water board in Dutch water management and an analysis of the current technological state of the art of Leeuwarden WWTP are presented. Further, the examination and analysis of the flow scheme of the energy, water streams and resources inputs and outputs are discussed. The foregoing will lead to the answer of the first sub-question.

2) **Understanding and Analyzing**: The research strategies of this stage are desk research and interviews with experts of the water board, related to technologies used and GHG emissions. Hence, a comprehensive analysis and classification of the current total GHG emissions of the WWTP is presented. This will provide the necessary knowledge and information to answer the second sub-question, with respect to the current total GHG emissions associated with the plant.

3) **Designing:** The goal of this step is to provide intervention solutions for the water board, based on the knowledge gained from the previous stages. The research strategy of the designing phase is interviews with experts, group focus and desk research. Regarding the interviews with experts, daily discussions occurred with members of the water board, which assisted in the formation of the analysis of the current total GHG emissions affiliated with the plant. Furthermore, the group focus method was used, where experts in the field were brought together in order to discuss and propose solutions regarding Climate Neutrality and the potential of capturing the carbon at the early stages of the wastewater treatment processes. The total number of participants was 9 and all of them are specialized in the water

sector (See appendix 1). Finally, desk research was conducted to verify and correlate the findings of the group focus and interviews with experts. Thus, the third sub-question, related to intervention solutions on reaching climate neutrality in the WWTP can be answered.

4) **Evaluation**: The aim of this stage is to provide conclusions based on earlier findings. The main question is answered by covering the three sub-questions and thus, a discussion related to the problem statement and the potential of Climate neutrality in the WWTP is included. Finally, recommendations for future research are provided.

1.6 Content Overview

The second chapter of this thesis includes the role and position of the water board, the current wastewater treatment technologies used and the flow scheme of the energy, resource and water streams inputs and outputs. The third chapter discusses the classification of GHG emissions affiliated with the water sector based on RVO (NL), IPCC, STOWA and other sources, the boundaries and the estimation of direct, indirect and biogenic emissions of the plant. The chapter concludes with a pie chart which includes all GHG emissions, which will be the baseline for the next chapter. The fourth chapter analyses the potential intervention solutions to reach climate neutrality at the WWTP in Leeuwarden by 2030 with negative emission technologies and by implementing the pilot project Core found. Finally, chapter 5 concludes this thesis by answering the main research question, discussing the results and setting the agenda for further research.

Chapter 2 State of the art of the WWTP

2.1 Introduction

This chapter starts with an analysis of the role and the position of the water board WF in Dutch water management. Further, the current treatment processes of the wastewater plant in Leeuwarden are described in order to have a better understanding of the water treatment system. This analysis also constitutes the first step in order to be able to examine the GHG released directly, indirectly and biogenically in the WWTP. Finally, a flow scheme of the energy, resources (chemicals) and water stream inputs and outputs during the wastewater treatment processes are presented and analyzed. Through these examinations, the first sub-question, "*What is the current technological state of the art of wastewater treatment plant in Leeuwarden?"* can be answered.

2.2 The role and position of the water board in Dutch water management

The water sector and its management play an essential role in Dutch society, being responsible for the safety, availability and cleaning of water. It is divided into three different organizations: a. Treatment companies (drinking water treatment and supply companies), b. the waste water distribution system (municipalities) and c. the wastewater treatment systems (water boards).

WF is the water board in the Dutch province of Friesland and a part of Groningen Westerkwartier. The core responsibilities of WF are qualitative and quantitative management of Friesland surface water, but also the care for the sea and polder dykes in the province. Therefore, the water board has categorized these tasks into three themes which are "Safety" (flood defense, dykes), "Availability of water" (water levels) and "Clean water" (treatment, ecology and swimming water). Regarding the treatment of wastewater, the water board uses 27 different WWTP throughout the province and it collaborates with the Friesland municipalities and other provinces (sewer systems).

This study focuses on the third theme, which is related to wastewater treatment processes, while the “safety” and the “availability of the water” are not included. Thus, it analyses the potential for climate neutrality of the WWTP in Leeuwarden as it is presented in the Climate Agenda and the Energy Policy of the water board (Arjan van den Hoogen, 2019).

2.3 The treatment processes of the WWTP in Leeuwarden

WWTPs are responsible for the treatment of municipal and industrial wastewater in order to return it to the environment with adequate quality (Bank, 2017). Although wastewater treatment processes have been characterized as energy-consuming and emitting industries, the processes are still based on the removal of solids, pollutants and nutrients, by breaking down organic matter and restoring the oxygen content of treated water. These processes traditionally are divided into primary treatment (pre-treatment), secondary treatment (normally biological treatment), post and tertiary treatment stages. As described below, in the case of Leeuwarden, sludge treatment and energy recovery are part of the plant as well.

The wastewater treatment processes start when the wastewater enters the installation. The supply of wastewater into the WWTP takes place with municipal sewage pumping stations and pressure pipes. The wastewater from surrounding villages is also provided through pumping stations and pipes into the WWTP. The total effluent supply is on average 44,061 m3/ day (1.6 Million m3/year) and the maximum capacity is 8,000 m3/hour (Documentation WF). The population equivalent for the WWTP in Leeuwarden is 182.484 habitants.

After the wastewater enters the plant, <u>the pre-treatment process</u> begins with mechanical screening (5% COD removal). The next step where the water passes is the selector, where the effluent meets the sludge (which has returned from the biological treatment process to the selector) and is mixed intensively. As a result, the organic compounds from the effluent are better absorbed by the sludge flocs, thus settable sludge can be formed during the purification process. Further, selector installation is provided with a bypass option to remove the gathered sand, in order to protect the pumps.

After the pre-treatment processes, the secondary (biological) treatment starts. The sewage water then, with the returned sludge, ends up in the 6 denitrification tanks, where the water from the aeration tanks is recycled. Denitrification process means that the nitrate and nitrite that have been formed in the aeration steps are converted from ammonia and organic nitrogen compounds into nitrogen gas, under free-oxygen conditions. Therefore, recirculation of the water occurs only if there is sufficient supply of wastewater unless the nitrate levels rise in this tank. For this reason, measuring and monitoring of nitrate levels can control recirculation processes. The WWTP in Leeuwarden uses 3 “Carousel” type aeration tanks for aeration with volume up to 9,105 m3 per tank. Further, Carousel type aeration tanks have 4,406 kg/day of BOD loading and 0.056 kg BOD/ kg dry sludge. After passing the denitrification tank, the sewage water is led to 3 aeration circuits. The content of the circuits is around 30,000m^3 per day. Oxygen is introduced into the water-sludge mixture through 12 surface aerators. Thus, the contamination from the bacteria is removed (oxidized). The aerators ensure the mixing of the water with activated sludge. The average time of the water in the aeration tank is slightly more than one day. The process of de-phosphating takes place after the oxidation. Through the biological treatment, a large amount of phosphate is captured. If there is more phosphate than normally expected in the water, iron is dosed in the denitrification tanks. In this stage, the concentration of phosphate is estimated to be the highest. Thus, the effective usage of chemicals can moderate them, while the iron binds the phosphate and is precipitated back in the sludge.

After the secondary (biological) treatment, the post-treatment follows. The cleaned sludge-water mixture enters the settling tanks (clarifiers) after the aeration process. The type of clarifier used in the plant is Circular Center Feed. In this stage, the purified water is separated from the settable sludge. The latter is discharged via the effluent line on the Wijde Greuns (the canal near the WWTP in Leeuwarden) while the settled sludge is mostly returned to the selectors and the denitrification tanks through screw pumps. Only a small amount of the sludge goes to the mechanical thickeners, this will be explained below, as sludge surplus.

Reaching the sludge process treatment, it is useful to mention that this sludge surplus has a dry matter content of around 0.8%. The volume of the dry matter content has to be further reduced so that the residence time in the fermentation tank can be increased. For this reason, the sludge is mixed with a polymer and then spread over a sieve cloth. Thus, the water runs through the screen cloth, leaving a drier sludge residue with a dry matter content of 7%. The type of sludge thickeners that are used is Bellmer Turbodrain TDC-3 with a capacity of 90m3/h for each of the mechanical thickeners and with an average sludge load of 10,098 kg ds/day. The sludge stream is introduced into the fermentation process (digestion) while the water returns to the aeration tanks. There are 2 fermentation tanks with a capacity of 4,700m3 each. After at least 20 days, and +/- 34°C, the sludge is fermented to an odorless black mass. Due to the fermentation, the sludge quantity is decreased around 25%.

This digestion process emits methane gas, which is primarily used for heating the fermentation tank. The biogas that is created supplies the 2 combined heat and power plants (CHP), which produce electricity for the WWTP, and residual heat for heating purposes. This stage is considered as the energy recovery stage in the WWTP. The type of CHP used is Mann E 2542 with a power capacity of 265 kW per installation (1.719 kWh/m3). Additionally, the methane gas which is generated is stored in a gas container. Finally, the digested sludge is pumped to the sludge buffer with a total capacity of 1000 m3. The sludge is periodically transported by lorry to the central sludge dewatering installation of WF in the city of Heerenveen. A charging station has been created for this reason in the Wijde Greuns. The sludge is pumped to this ship by a Netzsch pipeline type conveying pump with capacity 95 m3/h. Figure 1 below represents the mapping of the WWTP in Leeuwarden.

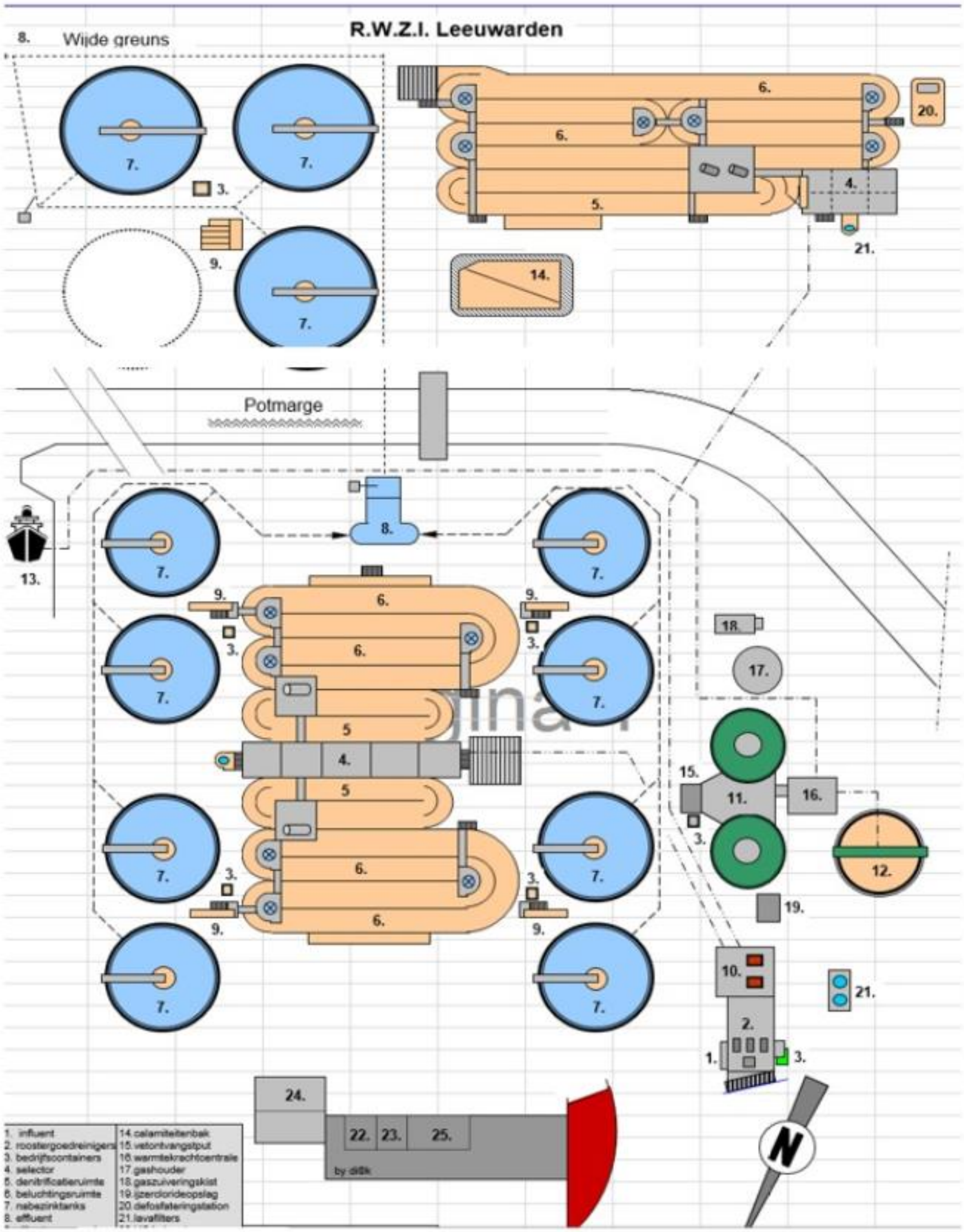

Figure 1. Schematic mapping of the WWTP in Leeuwarden

2.4 The energy, water streams inputs and outputs analysis of the wastewater treatment processes

The information of the table below is derived from WF documentation, data and through interviews with experts of the water board. In this stage, it is important to mention that, although this thesis is focused on the analysis of the GHG emissions in order to reach climate neutrality, the examination of the energy use in the wastewater treatment plant is crucial since energy usage is a significant contributor to the indirect GHG of the plant. Furthermore, the different units are all converted into GJ/year, if necessary. This means that the inputs and outputs of electricity (purchased and generated), presented in GWh/year, are converted into GJ/year by the conversion formula for energy which found 0.0036 GJ/ kWh (SI). The WWTP also produces biogas through the sludge treatments and digestion processes and this was calculated 1305621 million m3/year for the year 2018. The biogas line is divided into 81% at CHP motors, 6% supplying to building complexes, i.e. Fier (national center for abusement and violence in Leeuwarden) and Water Campus, 1.2% to heat the WWTP buildings and 11.8% is directed to the torch. Therefore, the conversion for the biogas inputs and outputs recorded on m3/year are based on the capacity of the gas motor in the WWTP in Leeuwarden which is 1,719 kWh/m3. Moreover, based on the data supplied by WF, 1,061,154 m3 of biogas is annually used by CHP facilities and correspond to 1.824.580 kWh/year. The 0.0036 GJ/kWh conversion was used again for the estimation of the total GJ/year derived from biogas at the WWTP. Beginning with the energy inputs of the WWTP, the total electricity needs are 17,638 GJ/year, where 62% is purchased from an electricity company (11,070 GJ/year) and the remaining 38% of its energy needs are generated by the plant through CHP facilities (6,568 GJ). It is also estimated that the motors are capable of generating around 30% of electricity and 70% of heat. This means that 1,979 GJ /year electricity and 4,598 GJ/year heat are generated to cover the energy needs of the plant. The heat generated by the CHP facilities is divided into 55% for heating purposes at the sludge treatment stage (2,529 GJ/year), 30% supplying the neighboring elderly house (Greunshiem), the (1,379 GJ/year) and 15% is considered as heat loss (690 GJ/year). The electricity is used mostly for the aeration processes, pumping, clarifiers and the digesters as can be seen in the figure below. The aeration process consumes around 70%

of the total electricity needs (12,308 GJ/year), while the remaining 30% is covered by the clarifiers, digesters and pumping processes. The annual influent that enters the plant is around 16 million m3 and the total sludge disposal is 55,598 tones/year.

Table 2. Calculations based on official documentation and literature review for energy inputs and outputs

		Conversion to GJ/year	
Total Biogas production - (100%)	1305621 m3/year		
- 12% Biogas to torch	155392 m3/year	962 GJ/year	
- 5.8% Biogas to Fier/Water Campus	73678 m3/year	456 GJ/year	
- 1.2% Biogas to buildings	15399 m3/year	95 GJ/year	
- **81% Biogas to CHP**	**1061154 m3/year**	**6568 GJ/year**	- 30% electricity **(1970 GJ/year)** - 70% heat **(4598 GJ/year)**
Total Electricity purchasing	**3075000 kWh/year**	**11070 GJ/year**	
Total Electricity consumption	**4899569 kWh/year**	**17638 GJ/year**	

In accordance with the calculations, the flow scheme of the energy inputs and outputs of the WWTP in Leeuwarden is presented. In this flow scheme, the usage of chemicals and its conversion into GJ and the inputs of external water and sludge streams are excluded. In the following figure, the blue arrow shows the electricity inputs-outputs, the orange arrows are the biogas inputs-outputs while green arrows are for heating sources. Finally, the black arrow symbolizes the waste sludge for disposal, which was also not converted into GJ/year.

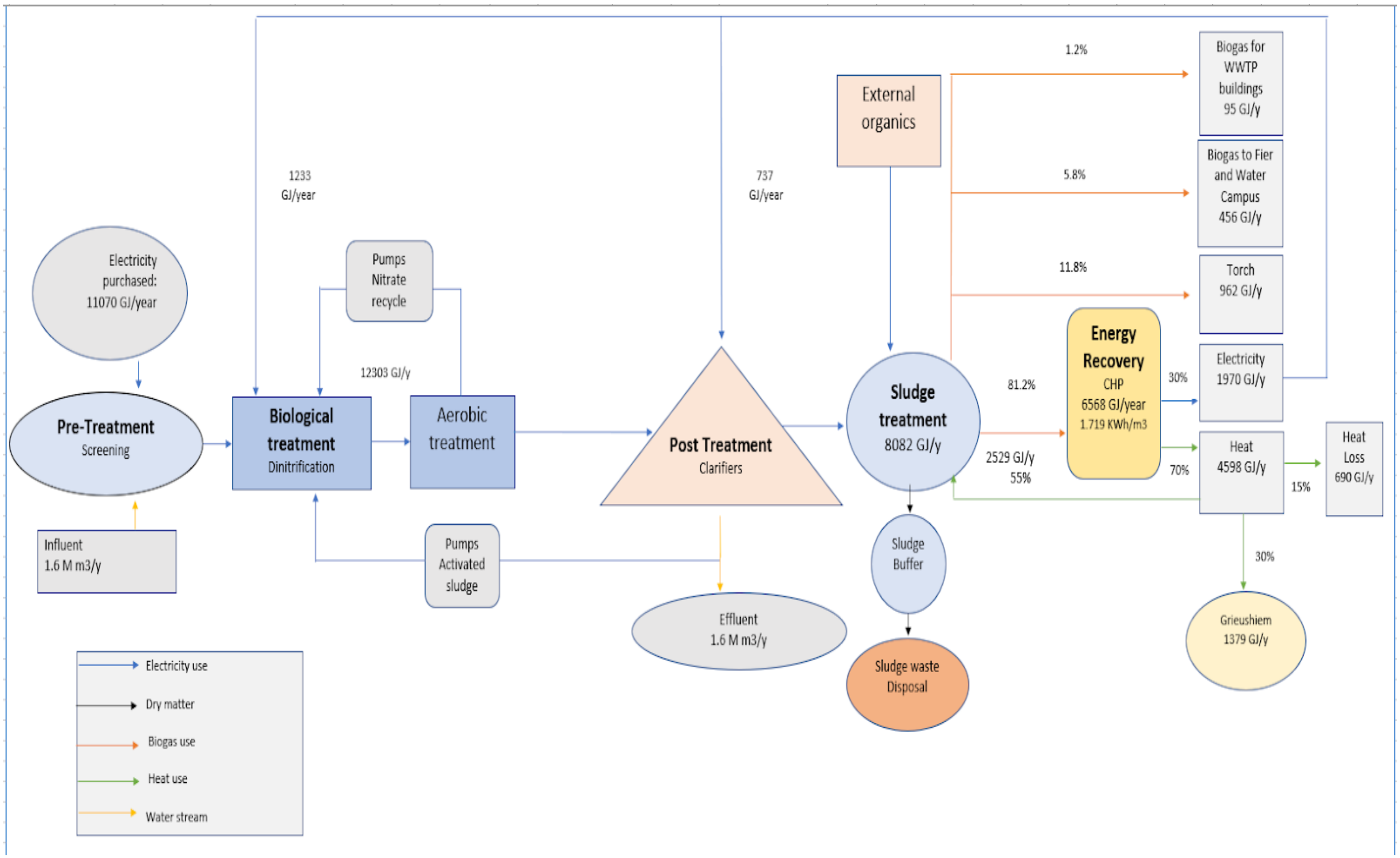

Figure 2 Flow scheme of energy use, water streams and resources, inputs-outputs, during the wastewater treatment processes.

2.5 Conclusion of the chapter

In this chapter, the state of the art of the WWTP in Leeuwarden is described and analyzed. This examination contributes not only to have a better understanding of the water treatment systems but also constitutes the first step in order to be able to examine the GHG released directly, indirectly and biogenically in the WWTP. Therefore, the first sub-question, "*What is the current technological state of the art of the WWTP in Leeuwarden?"* can be answered.

WWTPs are responsible for the treatment of municipal and industrial wastewater in order to return it to the environment with adequate quality (Bank, 2017). These processes traditionally are divided into primary treatment (pre-treatment), secondary treatment (normally biological treatment), post and tertiary treatment stages. In the case of Leeuwarden, sludge treatment and energy recovery are part of the plant as well. In the first stage of <u>pre-treatment</u>, mechanical screening takes place which is responsible for the removal of 5% of the total COD/year. Further, <u>the secondary (biological) treatment</u> starts. The sewage water ends up in the 6 denitrification tanks, where the water from the aeration tanks is recycled. The WWTP in Leeuwarden uses the "Carousel" type aeration tanks for aeration. After passing the denitrification tank, the sewage water is led to the aeration circuits. Oxygen is introduced into the water-sludge mixture through the surface aerators. Thus, the contamination from the bacteria is removed (oxidized). After the secondary treatment, <u>the post treatment</u> follows. The cleaned sludge-water mixture enters the settling tanks (clarifiers) after the aeration process. The type of clarifier used in the plant is Circular Center Feed. Additionally, <u>the sludge treatment</u> is the next stage of the wastewater management of the WWTP in Leeuwarden. The sludge is mixed with a polymer and then spread over a sieve cloth. The type of sludge thickeners that are used is Bellmer Turbodrain TDC-3. The sludge stream is introduced into the fermentation process (digestion) while the water returns to the aeration tanks.

This digestion process emits methane gas, which is primarily used for heating the fermentation tank. The biogas that is created supplies the combined heat and power plants (CHP), which produce electricity for the WWTP, and residual heat for heating purposes. This stage is considered as the <u>energy recovery stage</u> in the WWTP. The type of CHP used is Mann E 2542. Additionally, the methane gas which is generated is stored in a gas container. The sludge is periodically transported by lorry to the central sludge dewatering installation of WF in the city of Heerenveen.

In this stage, it is important to mention that, although this thesis is focused on the analysis of the GHG emissions in order to reach climate neutrality, the examination of the energy use in the wastewater treatment plant is crucial since the energy usage is a significant contributor to the indirect GHG of the plant. The energy analysis conducted, showed that the total electricity needs are 17,638 GJ/year, where 62% is purchased from an electricity company (11,070 GJ/year) and the remaining 38% of its energy needs are generated by the plant through CHP facilities (6,568 GJ). It is also estimated that the motors are capable of generating around 30% of electricity and 70% of heat. This means that 1,979 GJ /year electricity and 4,598 GJ/year heat are generated to cover the energy needs of the plant. The heat generated by the CHP facilities is divided into 55% for heating purposes at the sludge treatment stage (2,529 GJ/year), 30% supplying the neighboring elderly house (Greunshiem), the (1,379 GJ/year) and 15% is considered as heat loss (690 GJ/year). The electricity is used mostly for the aeration processes, pumping, clarifiers and the digesters as can be seen in the figure below. An essential point is that the aeration process consumes around 70% of the total electricity needs (12,308 GJ/year), while the remaining 30% is covered by the clarifiers, digesters and pumping processes. The annual influent that enters the plant is around 16 million m3 and the total sludge disposal is 55,598 tones/year.

Chapter 3 Analysis of GHG emissions in the WWTP

3.1 Introduction

With respect to the goal of reaching climate neutrality by 2030, the examination and the estimation of the GHG released during the treatment processes are analyzed. Thus, in this chapter, scientific literature and official documents are reviewed (organizational reports and data) in order to determine which, where and how much GHG are emitted in the WWTP of the city of Leeuwarden. Further, an overview of the WWTP carbon footprint is presented and analyzed after defining the boundaries of the GHGs estimation and their classification.

3.2 Classification of GHG emissions

Water resource recovery facilities release gases such as nitrous oxide (NO_2), carbon dioxide (CO_2) and methane (CH_4) which essentially contribute to global warming (GWRC, 2011; Law et al., 2012; Sweetapple et al., 2014; Parravicini et al., 2016). The GHG released in the WWTP are categorized into three Scopes. The direct anthropogenic (Scope 1), indirect internal (Scope 2) and indirect external (Scope 3) emissions of an industrial plant as characterized in the General Reporting Protocol for Climate Registry by the United Nations (2013).

Scope 1 includes the direct greenhouse gas emissions which occur from sources that are owned or controlled by the company, while the CO_2 emissions from combustion of biomass, which is produced on-site, are excluded from this scope. Specifically, direct emissions from WWTPs derive from biological carbon, nitrogen and phosphate removal processes and sludge management. The CO_2 is emitted from organic matter degradation, N_2O from nitrification and denitrification and CH_4 from anaerobic digestion. Scope 2 consists of the GHG emissions that occur from the use of electrical and thermal energy, as defined by the Greenhouse Gas Protocol Initiative, 2004. Scope 3 constitutes other indirect GHGs which are accountable to emissions from sources that are not owned or controlled by the company (World Business Council for Sustainable Development, 2014). Moreover, the Intergovernmental Panel on Climate Change in the Guidelines for National Greenhouse Gas Inventories (2019) also clarified the need for tracking and reporting biogenic CO_2 emissions separately from the other emissions due to the origin of the organic matter. Elements of carbon in biomass were contained in living organic matter. This means that the carbon is not derived from fossil fuels, which creates the need for a different method for calculating and classifying carbon. This method (CO_2 emissions from biomass combustion) applies only to CO_2 and not to CH_4 and N_2O, although these are also emitted during biomass combustion. This happens due to the non-biogenic origin of CH_4 and N_2O, unlike CO_2, and thus these emissions are categorized into Scope 1.

3.3 Definition and boundaries of Carbon Footprint of the WWTP

There are several different methodologies available to determine a carbon footprint such as IPCC-2006, WSAA-2006, LGO-2008, Brindle-2008, NGER-2009, GWRC-2011 (Pagilla et al., 2009). However, after evaluating these methods, it was verified that the total carbon footprint of a WWTP cannot be calculated by using only one of these methods, since these require on-site measurements and calculation of actual GHG emissions based on an annual time frame. Therefore, different approaches had to be combined in order to define and calculate the current carbon footprint of the WWTP in Leeuwarden. The informative value of carbon footprint examination is based on a well-selected use of emission factors for the calculations. Various databases and sources are presently accessible, mostly for indirect anthropogenic emissions (INCOPA, 2014; SimaPro, 2007, STOWA, 2014). For direct emissions of CH_4, few research and measurements have been identified while the examination of N_2O emissions from activated sludge processes has been intensively analyzed throughout the last decade. Nevertheless, the decision on a representative emission factor of N_2O is still debatable due to the broad variety of the results (Parravicini et al., 2016). Due to the time limit of the thesis, non-experimental analysis and monitoring of data was conducted, the presented values are thus based on different emission factors found in the literature and after consultation with WF experts.

Subsequent to the life cycle approach, the carbon footprint in this study is defined as direct anthropogenic, indirect anthropogenic and biogenic GHG emissions caused by a defined system boundary. The accounted GHG emissions including biogenic and anthropocentric emissions of CO_2, CH_4 and N_2O are all converted into carbon dioxide equivalents (CO_2-eq.) by global warming potentials (GWPs) over a 100 year time horizon (IPCC, 2014; Parravicini et al., 2016). Particularly, the equivalence is 1 for CO_2, 25 for CH_4 and 265 for N_2O, as defined by the Fifth Assessment Report of the GHG protocol in 2013 (AR5). At this point, it is essential to clarify that in the main operation of the WWTP, the biogenic carbon of wastewater is 1) oxidized to CO_2, 2) incorporated into biomass, 3) burned by the torch and 3) produced by CHP facilities (Campos et al., 2016). It is noted that CO_2 emissions from biological wastewater treatment are generally not considered in the carbon footprint of WWTP because it has not a fossil origin (Parravicini et al., 2016).

However, some studies have pointed out that around 20% of the carbon present in wastewaters can be of fossil origin and fossil CO_2 emissions from wastewater treatment are underestimated. In this study, they are therefore taken into consideration when quantifying and qualifying the associated CO_2 emissions (Rodriguez et al., 2012; Law et al., 2013; Griffith et al., 2009; Chunyan Chai et al., 2015). Finally, direct emissions, such as employees commuting and indirect emissions derived from the sewer system and remained in the effluent, the emissions from the materials used for the construction of the WWTP, and GHG emissions that occur during transportation of the chemicals that are used in the WWTP are excluded from this study.

Thus, based on the above mentioned boundaries and the definition of the carbon, the categories of GHG emissions in this thesis are defined in the following way:

1) **Indirect Anthropogenic Emissions** are those which are emitted off-site the plant and derived from the transportation of trucks and lorries for the sludge management, pre-treatment, dewatering of sludge, electricity purchasing and chemicals used.

2) **Direct Anthropogenic Emissions** are those which are released on-site and are created due to wastewater treatment facilities such as N_2O from nitrification, denitrification processes and CH_4 from sludge management.

3) **Biogenic Emissions** are those which are released on-site but the origin of the CO_2 is not from fossil fuel. The processes in the WWTP that emit biogenic CO_2 emissions are during the aeration process, the digestion, the torch and the combustion of biogas on CHP motors.

These are analyzed in depth below based on the schematic analysis of the qualified Figure 3. This illustrates the aforementioned GHG emissions based on the 3 different categories defined. The GHGs released are presented based on the treatment processes. The green color indicates the indirect anthropogenic emissions, red the direct anthropogenic while blue is for biogenic emissions of carbon.

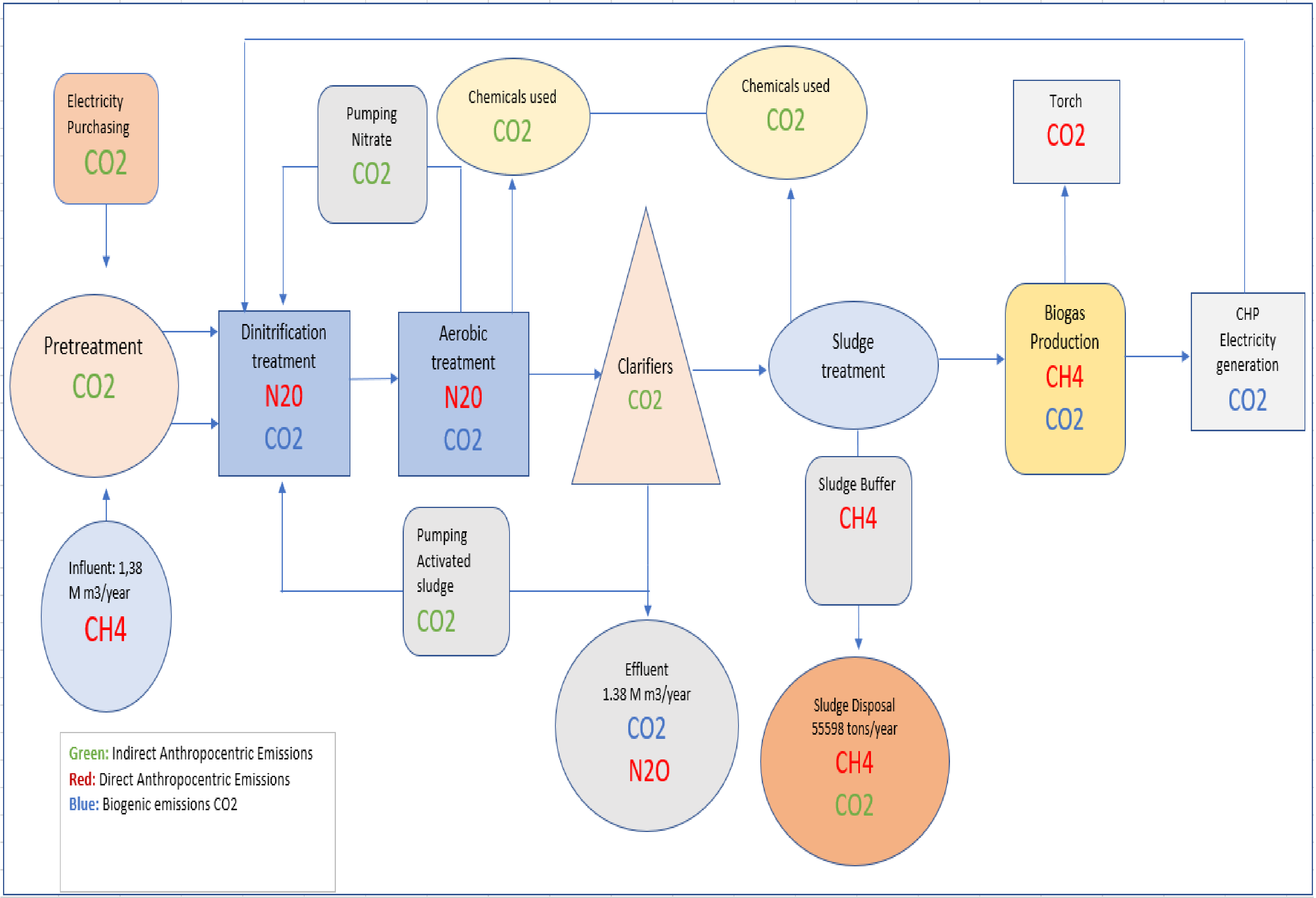

Figure 3. Schematic analysis of the GHG associated with the plan-system boundaries.

3.4 Indirect Anthropogenic Emissions

This sub-chapter includes the analysis and calculation of the indirect anthropogenic emissions, namely, from the usage of the chemicals, the electricity consumption and sludge disposal, relying on literature review and official documentation.

3.4.1 CO_2 from Chemicals used

Adding chemicals to the wastewater during the treatment processes has an indirect effect on CO_2 emissions since the production of chemicals leads to a release of CO_2 (Snip, 2010). This means that although these emissions are generated off-site of the WWTP, they are included in this study, based on the boundaries defined in paragraph 3.3. The estimation of the CO_2 emissions derived from the addition of chemicals is done by calculating the tones of chemicals used yearly (official document WF, 2016). Based on that, the calculation of the electricity consumed in Megajoules, for each different chemical relied on governmental emission factor list (RVO.nl, 2018). Finally, the amount of CO_2 emissions found is based on the emission factor of primary energy of national standards. (RVO.nl, 2014). The usage of chemicals in the WWTP is mostly related to the polyelectrolyte emulsion (50%) and the iron dosing, where 11.96 tons PE/year 45.6 tones FeSO4/year and 143 tones FeClSO4/year are used respectively. Based on the Brandstoffenlijst, the dutch governmental list for estimating GHG emissions, one kilo of the polyelectrolyte emulsion is the equivalent to 64.45 Megajoule. Thus, 770.822 MJ/year are consumed for the usage of polyelectrolyte emulsion, leading to 43 tons of CO_2 per year. Further, dosing of iron is contributing to GHG emissions since the 45.6 tones FeSO4/year used are equivalent to 155.040 MJ/year. This according to Rijksdienst voor Ondernemend Nederland (RVO.nl, 2019) with an emission factor of 3.4 MJ/kg of FeSO4, means equivalent 9 tons CO_2/year. To this effect, 143 tons of FeClSO4 is equal to 99 tons CO_2/ year, under the emission factor of 12.3 MJ/kg. Thus, the total annual estimated CO_2 emission from the usage of chemicals in the WWTP is 151 tones. As stipulated in paragraph 3.3, the CO_2 released due to the transportation of chemicals is not included in the estimation of the total carbon footprint of the WWTP in Leeuwarden.

3.4.2 CO_2 from Electricity used

The WWTP high energy demand, which is currently purchased mostly from the electricity grid (60% of the total energy needs), makes the plant a significant contributor to the indirect greenhouse gas emissions (Sweetapple et al., 2014). In most WWTPs operated with activated sludge processes, aeration commonly accounts for around 50-60% of the total electricity consumption. The remaining 40% is divided into 15-25% being 15% for the sludge treatment and 25% for the secondary sedimentation (including recirculation pumps) respectively (Mamais et al., 2015). In the case of Leeuwarden, the aeration process consumes 70% of the total electricity usage. It is essential to clarify that a total number was estimated for this research, related to the CO_2 emissions from the electricity purchased and not separately for aeration, pumping, sludge management and sedimentation. As mentioned in paragraph 2.3, the electricity purchased from the electricity grid is estimated in 3.075 GWh per year. Although WF has a green certification and guarantees the origin of the purchased electricity, the estimation of the CO_2 emissions due to the energy usage, in this study, relies on the emissions factor of grey electricity consumption in The Netherlands (RVO.nl, 2019), where 1 kWh is equivalent to 649 g CO_2. This results from the need for estimating the CO_2 derived from electricity usage despite the possession of the green certification. Therefore, it occurs that 1.996 tones CO_2 are emitted annually due to electricity purchasing. It is important to mention that 40% of the plant's electricity needs are covered by the biogas production on-site. This generated biogas, is used to replace the purchasing of electricity from the grid. Through the biogas conversion in the gas motors, CO_2 is also emitted (Snip, 2010). However, these CO_2 emissions are considered biogenic emissions and are analyzed in the relevant sub-chapter below.

3.4.3 CO_2 from Disposal of sludge

With the completion of sludge treatment processes, the remaining fraction is transported to the city of Heerenveen for dewatering. This contributes twice to the Carbon footprint of the WWTP in Leeuwarden. Firstly, indirect emissions related to the transportation of the sludge to Heerenveen and secondly, the dewatering process itself consists of chemical use and electricity consumption, which are included as contributing factors in this research. Furthermore, the final dewatered sludge is finally sent to an incineration site, N.V. Slibverwerking Noord-Brabant, SNB. Therefore, the emissions correlated to the transportation of sludge to SNB are also part of this thesis and analyzed below.

- **CO_2 from the transportation by a lorry of sludge to Heerenveen**

Based on data supplied by WF, 55.400 tons of sludge are transported annually to Heerenveen by ships. The distance from the Leeuwarden plant to Heerenveen is estimated at 32 kilometers and 56 trips are recorded annually for this purpose. Thus, 1.773 km/year are covered for sludge transportation. Based on a governmental paper, 41 g CO_2 /ton-km are emitted, which means that 73 tons of CO_2 per year are added in the total GHG emissions estimation of the WWTP in Leeuwarden (Pradel & Reverdy, 2012; RVO.nl, 2018).

- **CO_2 from dewatering of sludge at Heerenveen**

Apart from the emissions accounted for transportation, the process of dewatering the sludge that takes place in Heerenveen also contributes to CO_2 emissions from the indirect chemical used and electricity consumption. According to the organizational document of WF, it is found that the share of Leeuwarden is 14% of the total sludge dewatering processes done in Heerenveen.

It is necessary to include the usage of chemicals in this 190 tones polyelectrolyte emulsion and 1985 tons FeCl which were estimated for dewatering purposes in 2018. Based on the aforementioned calculation of chemical used as outlined in paragraph 3.4.1, it is found that 190 tons of polyelectrolyte emulsion are responsible for 1700 GJ, while 4400 GJ is derived from the FeCl dosing. This means the CO_2 released by the usage of chemicals is estimated 95 tones and 252 tons CO_2 annually for polyelectrolyte emulsion and FeCl dosing respectively. The emission factor of primary energy is 56.1 kg CO_2/GJ and the total electricity used for this process is 0.85 GWh/year which means that the CO_2 emissions from the electricity use are 77 tons CO_2/year (Pradel & Reverdy, 2012).

3.4.4 CO_2 from the transportation of sludge to SNB

SNB operates the largest incineration plant in The Netherlands. The company receives municipal sewage sludge from six different water boards, one of WF. Based on official documentation, the dewatered sludge mass (sent to incineration) from Leeuwarden, accounts for 11.357 ton/year. The distance from the WWTP to SNB is 240 km and the total trucks used annually are 379. Thus the total ton*km is 2.725.680. The emission factor of CO_2 for ton*km is 115 g CO_2/ton km (RVO.nl, 2018). Therefore, 313 ton CO_2/year are emitted due to the sludge transportation by trucks.

3.4.5 CO_2 from pre-treatment

As mentioned, the pre-treatment of the WWTP in Leeuwarden is based on mechanical screening which is able to remove 5% of the total COD generated annually. Based on organizational documentation, it was found that 7446 tons COD/year enter the plant and 372 tons COD/year (5%) ends up in the incineration facilities. Although these emissions are not released on-site, they are released during the incineration process and therefore, indirect emissions are estimated due to pre-treatment process. According to SNB report (2015) and IPCC, it was found that for the incineration of sewage sludge in fluidized-bed plants, an emission of 1 Mg of CO2 per Mg of incinerated sludge (dry matter) is estimated. This leads to the calculation of the biogenic emissions released by incineration due to pre-treatment up to 327 tons CO2/year.

Figure 1 shows the indirect emissions associated with the WWTP in Leeuwarden. As described, from the total 3284 tons CO2 61% derives from the electricity purchased, which is used mostly for aerobic processes, 13% from dewatering the sludge, 10% from pre-treatment and incineration, 9% from transportation with trucks to SNB incineration company, 5% from chemical used and 2% from transportation with lorries to Heerenveen.

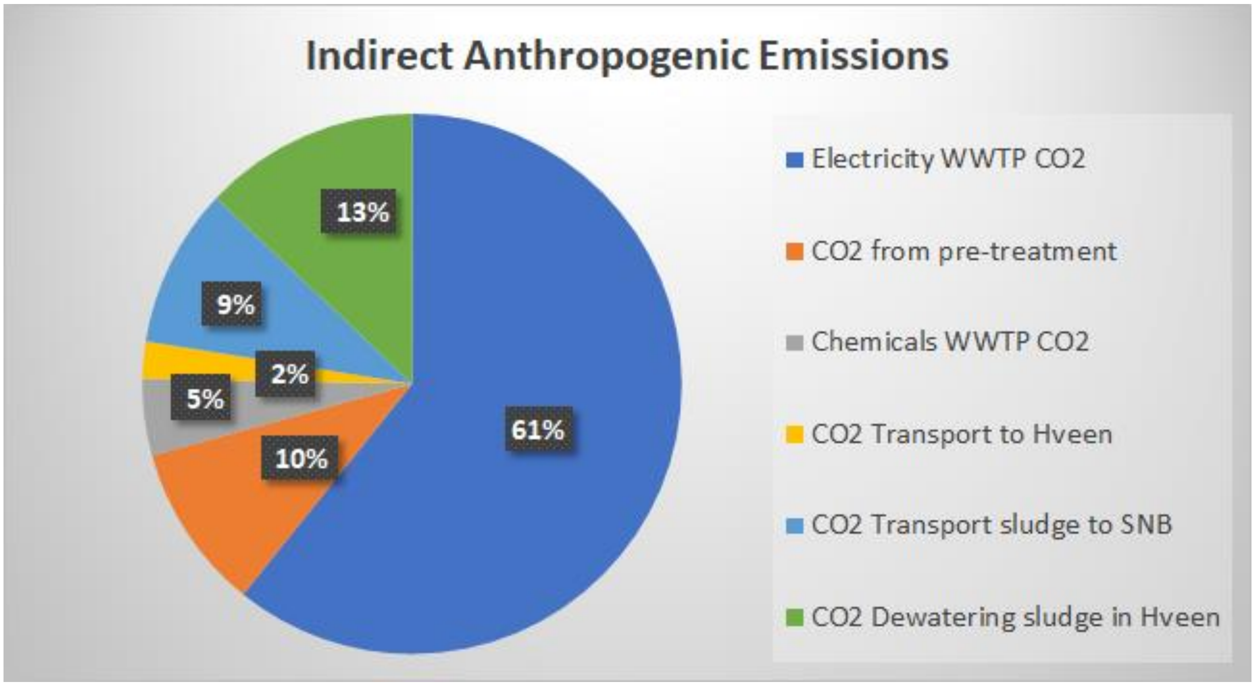

Figure 4. Pie chart of Indirect Anthropogenic emissions in the WWTP.

3.5 Direct Anthropogenic Emissions

This sub-chapter analyzes the direct anthropogenic emissions from N_2O production and CH_4 production in the WWTP.

3.5.1 N_2O emissions from nitrification/denitrification process

N_2O is released by nitrification and denitrification processes used to nitrogenous mixtures removal from the wastewater, but N_2O is also produced due to chemical reactions. Nitrifying bacteria produce N_2O under aerobic or anoxic conditions (Campos et al., 2009). The N_2O emissions are mostly derived from the activated sludge units (90%), while the remaining comes from the grit and sludge storage tanks (Campos et al., 2016; Czepiel et al., 1995). Virtually, nitrous oxide is released in the aerobic tank of the WWTP. However, the precise contribution of N_2O emissions is still ambiguous, since it can be striped to the gas phase in the aerated compartments. (Campos et al., 2016)

In order to calculate the contribution of N_2O in the total GHG emissions of the WWTP, firstly the total water flow was calculated and it was found to be 16 million m3 per year. It is also known from the official documentation that the concentration of nitrate in the water is 39.6 mg-N/liter and that the total N_2O-N is 1.57 tones per year. Based on the STOWA report, and its assessment for the WWTP operation in Leeuwarden, the emission factor was found to be around 0.05%. Further, according to the Fifth Assessment Report of the GHG protocol, the global warming potential value for a 100-year time horizon of nitrous oxide is 265 times CO_2 equivalent. Thus, although the total tons of N_2O are only 1.57 tones/year the relative CO_2 equivalence is calculated on 133 tons CO_2/ year. It is important to mention that the given emission factor is extremely low, which means that if a higher emission factor is taken into account, i.e. 0.5%, then the contribution of N_2O in the total carbon footprint changes drastically with an estimation of 1.336 ton CO_2 eq/year.

3.5.2 CH_4 emissions from sludge treatment

Based on Daelman et al. (2012) and Kwork et al. (2015), the main sources of CH_4 are associated with the sludge treatment where anaerobic digestion occurs at the primary sludge thickener, the centrifuge, the exhaust gas of the CHP, the buffer tank of digested sludge and the storage tank for the dewatered sludge. These concentrations of CH_4 emitted cover around 70% of the total CH_4 emissions in the WWTPs. The remaining derives from the biological treatment where dissolved CH_4 partly remains after the treatment processes (Campos et al., 2016).

The estimation of methane emissions at the plant is based on the latest STOWA report of 2016 with respect to methane emissions in the WWTPs. An emission factor of 113 kg CH_4/day is estimated for a population equivalent of 100.000. This means that the calculation is based on the total CH_4 emitted annually and there is no further analysis on the CH_4 emissions per installation of the different treatment process. The population equivalent of the wastewater of the WWTP of Leeuwarden in 2018 was 182.484 which means that 206 kg CH_4/day are released. In accordance with the organizational documentation, 75 tons of CH_4 emissions were detected in 2018. However, based on the fifth Assessment Report of GHG protocol, the global warming potential for 100-year time horizon is estimated 25 tons CO_2 equivalent per ton CH_4. Thus, a significant contribution of 1.882 tons CO_2 eq/ year is estimated.

The Figure below shows the total direct anthropogenic emissions as described above. The total amount was estimated 2014 tons CO_2 eq/year. The contribution of the CH_4

emissions due to sludge management is considerable, covering 93% of the total direct emissions while 7% of CO_2 equivalence N_2O derives from nitrification and denitrification process. Although the CH_4 emissions seem to be high, there are not specific calculations per different CH_4 emitting process. However, it is known from interviews with experts and literature review that sludge buffer is the most CH_4 emitting process. Further, although the contribution from N_2O is considered very low due to the emission factor of STOWA (0.05%), more investigation is currently taking place by WF experts regarding the precise N_2O emissions.

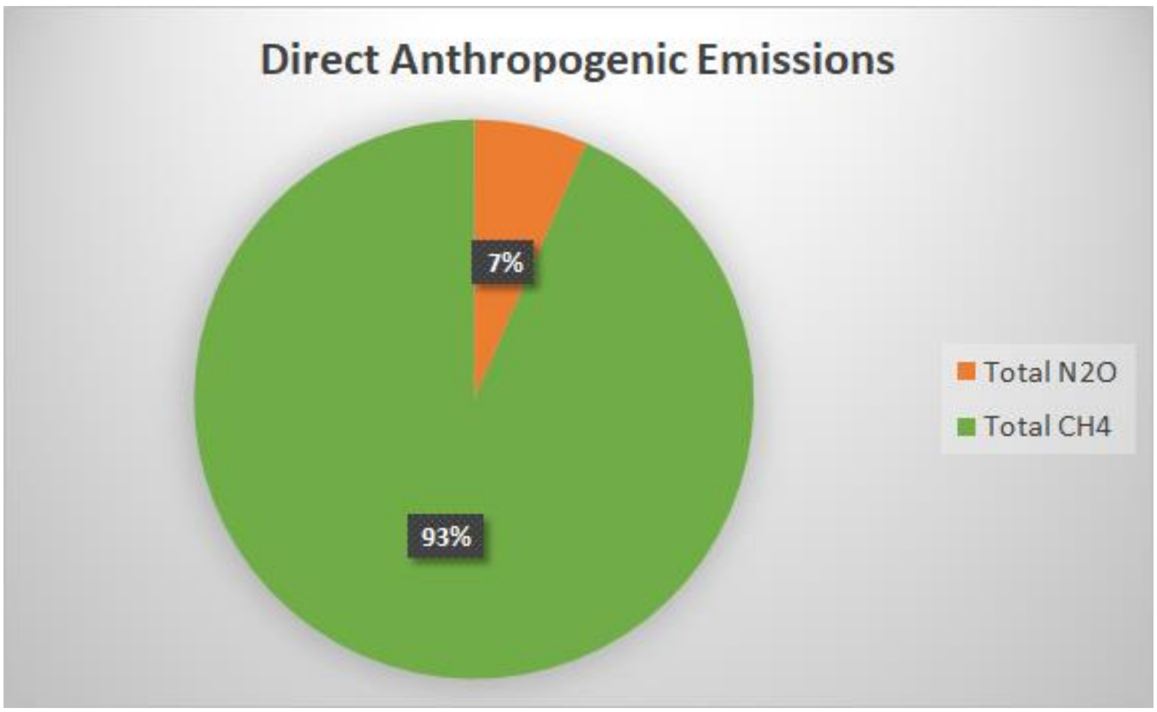

Figure 5. Pie chart of direct anthropogenic emission of the WWTP

3.6 Biogenic CO_2 emissions

CO_2 generated during the wastewater treatment was defined as biogenic and was not included in carbon footprint analyses since it was not accounted for as emissions under the current carbon accounting rules (EPA, 2018). However, under the current system municipal wastewater is treated with conventional activated sludge process. Therefore, the carbon in wastewater is not fully recovered but partially oxidized into CO_2. This process requires intensive aeration to allow the mineralization of organic matter and the production of effluent under the legal requirements with respect to water content. These emissions are also emitted by the anaerobic digestion of biogas, the usage of the torch and the combustion of biogas in the CHP motors and are analyzed below.

3.6.1 CO_2 emissions from aerobic treatment

The aerobic process taken place during the biological treatment releases biogenic CO_2 in addition to this emitted due to electrical consumption (Byrns et al., 2013). According to STOWA report (2014), these biogenic CO_2 emissions can be calculated based on the COD influent, the COD efficiency, the annual effluent and the emission factor 1.2 kg CO_2/kg COD. Therefore, it was found that the influent COD concentration is 441 mg/l and the efficiency accounts for 92%, while the total effluent flow is 16.082.265 m3/year. Thus, the total COD flow is 7.092 tons per year and after implementing the emissions factor mentioned (1.2 kg CO_2/kg COD), one can estimate that around 8.051 tones biogenic CO_2 emissions are associated annually with the aeration process.

3.6.2 CO_2 emissions from anaerobic digestion

The biogas generated by the anaerobic digestion processes on-site is mostly composed of methane and carbon dioxide and lower percentages of hydrogen sulfide and ammonia. Based on Makisha and Semenova (2018), biogas is a mixture of 50-70% of CH_4 and, 30-40% of CO_2. In this research, the calculation is based on the proportion of 65% CH_4 and 35% CO_2. This means that from the total biogas production, which is 1.305.621 m3/ year, and their molar ratios, the mass composition of dry biogas at standard temperature and pressure is 685 g CO_2/m3 (Bryns et al, 2013), occurs thus that 313 tons CO_2/ year is produced in the anaerobic digestion process. It is important to mention that the emissions derived from the CH_4 combustion are not calculated separately in this study. The CO_2 eq from CH_4 emissions is calculated totally as described in paragraph 3.5.2.

3.6.3 CO_2 emissions from CHP

As mentioned in paragraph 2.4, the operation of the WWTP is based on 40% of the energy needs on the cogeneration facilities. The total biogas production of the plant is 1.305.621 m3/year, however, 81% accounts for CHP usage. This means that 1.061.154 m3/year are used in order to generate electricity and heat by the cogeneration facilities on-site. The capacity of the current engines is 1.719 kWh/m3 while the 3.6 MJ/kWh conversion is used for the calculation of the total GJ/year consumed from CHP facilities. Further, based on RVO.nl (2018), the emission factor of biogas produced by WWTPs is estimated to be 84.2 kgCO_2/GJ. This means that the biogenic CO_2 associated with CHP facilities are an estimated 553 tons CO_2/year.

3.6.4 CO_2 emissions from the torch

It is estimated that 12% of the total biogas production is burned by the torch. The classification of the specific emission was debatable since the burning fuel is biogas produced by the sludge but also takes place on-site the. Based on the classification and the boundaries defined, it is considered as biogenic emission. The calculation is based on the national emission factor list, which estimates an emission factor of 1.962 kg CO_2/m3 biogas (RVO.nl, 2018). This leads to the calculation of the 524 tons CO_2 emitted due to the torch annually.

Figure 3 describes the biogenic emissions released during the treatment processes where 86% derives from aeration processes, 3% from digestion, 6% from CHP facilities and 5% from the torch. It can be concluded that the contribution from the aeration process during the biological treatment is essential. Further, based on this analysis the total biogenic emissions were an estimated 10228 tons CO_2/year.

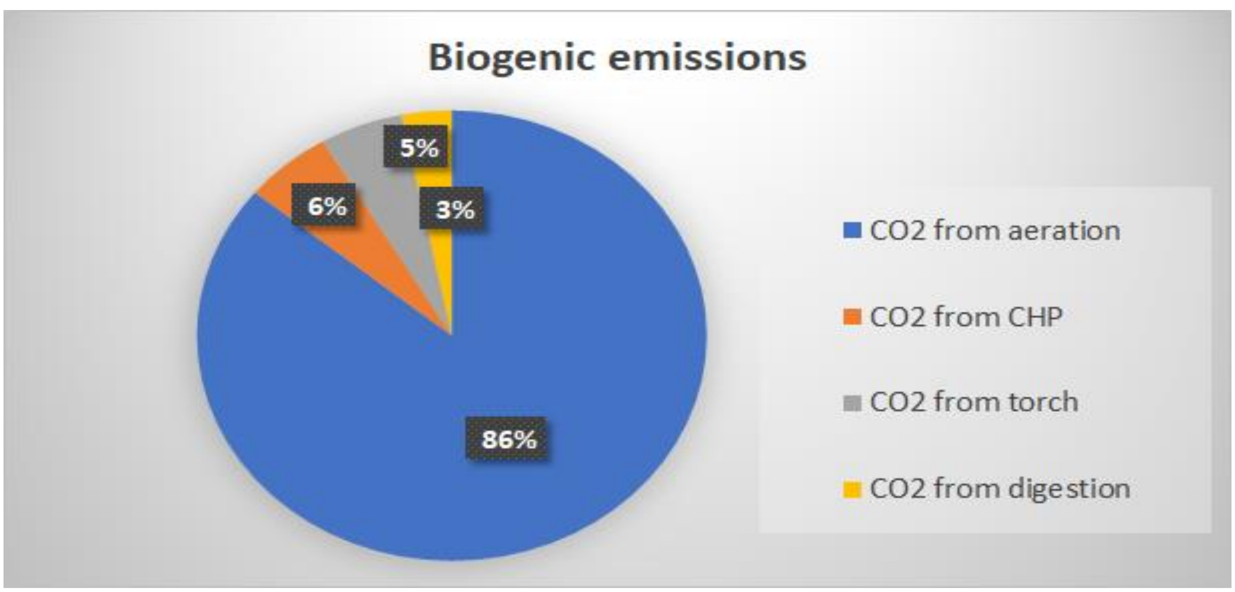

Figure 6. Pie chart of Biogenic CO_2 emissions of the WWTP

3.7 Conclusion of the chapter

In this chapter, the examination and the estimation of the GHG released before, during and after the treatment processes are analyzed, in order to determine which, where and how much GHG are emitted in the WWTP of the city of Leeuwarden. Subsequent to the life cycle approach, the carbon footprint in this study is defined as direct anthropogenic, indirect anthropogenic and biogenic GHG emissions. The accounted GHG emissions including biogenic and anthropocentric emissions of CO_2, CH_4 and N_2O were all calculated and converted into carbon dioxide equivalents. Therefore, the second sub-question "*What is the current emission of GHG in the WWTP in Leeuwarden?*" can be answered as shown below.

Indirect Anthropogenic Emissions are those which are emitted off-site the plant and derived from the transportation of trucks and lorries for the sludge management, pre-treatment, dewatering of sludge, electricity purchasing and chemicals used.

Table 3. Estimation of the direct anthropogenic emissions associated with the WWTP.

Classification of GHG	**Unit**	**Emission Factors**	**Calculation**	**Reference**
Direct Anthropogenic				
N_2O	Tons CO_2eq/year	- 0.05% ton N_2O/year - 265 ton CO_2 eq/ton N_2O	133	-STOWA (201) - GWP (2015)
CH_4	Tons CO_2eq/year	-113 kg CH_4/day/100.000 PE -25 tons CO_2 eq/ ton CH_4	1882	-STOWA -GWP
Total direct	**Tons CO_2/year**		**2014**	

Direct Anthropogenic Emissions are those which are released on-site and are created due to wastewater treatment facilities such as N_2O from nitrification, denitrification processes and CH_4 from sludge management. The table below summarizes the estimations of paragraph 3.

Table 4. Estimation of the indirect anthropogenic emissions associated with the WWTP.

Classification of GHG	**Unit**	**Emission Factors**	**Calculation**	**Reference**
Indirect Anthropogenic				
CO_2 Transportation to Heerenveen	Tons CO_2/year	-39 g CO_2/ ton-km with a lorry	73	RVO.nl
CO_2 Transportation to SNB	Tons CO_2/year	-115 g CO_2/ ton-km	313	RVO.nl
CO_2 Dewatering of Sludge Heerenveen	Tons CO_2/year	-0.649 kg CO_2/kWh Country specific	425	VENM.nl, 2018
CO_2 from pre-treatment	Tons CO_2/year	-1 kg CO_2/kg COD	327	STOWA
CO_2 Electricity purchased	Tons CO_2/year	-0.649 kg CO_2/kWh Country specific	1996	VENM.nl, 2018
CO_2 from Chemicals used	Tons CO_2/year	-56.1 kg CO_2/ GJ - Iron chlorosulfate 12.3 MJ/kg - Iron sulfate 3.4 MJ/kg - Polyelectrolyte 64.45 MJ/kg	151	RVO.nl, 2015
Total indirect	**Tons CO_2/year**		**3285**	

Biogenic Emissions are those which are released on-site but the origin of the CO_2 is not from fossil fuel. The processes in the WWTP that emit biogenic CO_2 emissions are during the aeration process, the digestion, the torch and the combustion of biogas on CHP motors.

Table 5. Estimation of the biogenic emissions associated with the WWTP.

Classification of GHG	**Unit**	**Emission Factors**	**Calculation**	**Reference**
Biogenic emissions of carbon				
CO_2 from aeration	Tons CO_2/year	-1.2 kg CO_2/kg COD	8511	STOWA
CO_2 from digestion (35%)	Tons CO_2/year	-685 kg CO_2/ m3	313	Bryns et al, 2013
CO_2 from CHP	Tons CO_2/year	-84.2 kg CO_2/GJ Country specific	553	RVO.nl, 2018, 2005
CO_2 from torch	Tons CO_2/year	-1.962 kgCO_2/m3 Country specific	524	RVO.nl, 2018
Total biogenic	Tons CO_2/year		**10228**	
Total GHG emissions	Tons CO_2/year		**15200**	

With respect to the analyses of paragraphs 3.3-3.6, the following pie chart represents the total direct, indirect anthropogenic and biogenic emissions of the WWTP in Leeuwarden. The fact that the total biogenic emissions cover 65% of the total emissions associated is considerable. Based on paragraph 3.4, it seems that the aeration process generates the highest amount of GHG. Around 61% of the total of 3284 tons indirect emissions derive from electricity used. This is one useful piece of information in order to calculate the emissions derived from the aeration process, taking into consideration that 70% of the total electricity is consumed by the aeration process. This means that 1397 tons of indirect CO_2 per year are released from the aeration process alone. Moreover, paragraph 3.6 shows that 86% of the total biogenic emissions is released by the aeration processes in the biological treatment. This shows that additional 8511 tons biogenic emissions are released by the aeration process. Therefore, the total amount of emissions associated were an estimated 10228 tons of CO_2. However, the direct emissions are responsible for 13% of the total emissions (red shades in the pie chart) and the indirect emissions cover an additional 21% (green shades in the pie chart), while the rest 66%(blue shades in the pie chart) is considered as biogenic emissions.

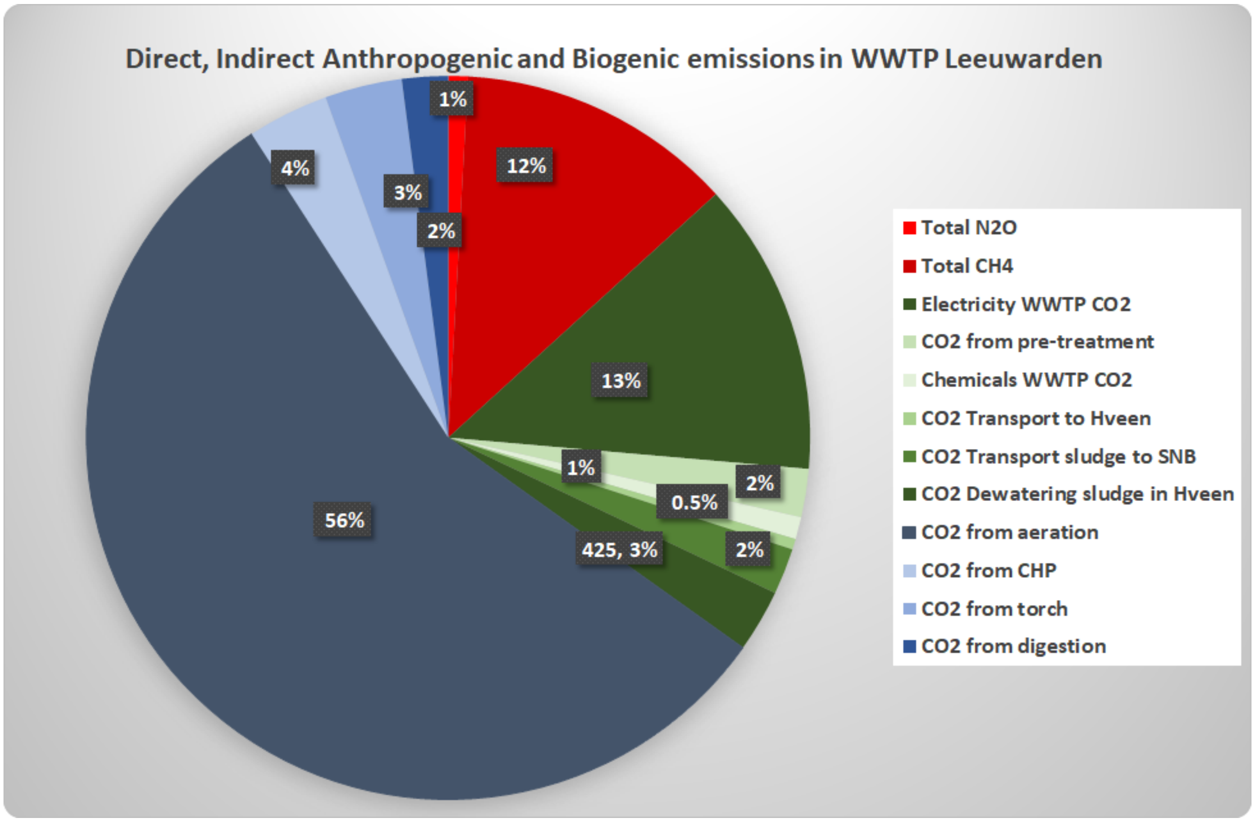

Figure 7. Pie chart of total direct, indirect anthropogenic and biogenic emissions of WWTP

The table below summarizes all the emission factors used and the relating calculation of the direct, indirect anthropogenic and biogenic emissions associated with the WWTP.

Table 6. Estimations of the direct, indirect and biogenic emission based on literature.

Classification of GHG	Unit	Emission Factors	Calculation	Reference
Direct Anthropogenic				
N_2O	Tons CO_2eq/year	- 0.05% ton N_2O/year - 265 ton CO_2 eq/ton N_2O	133	-STOWA (201) - GWP (2015)
CH_4	Tons CO_2eq/year	-113 kg CH_4/day/100.000 PE -25 tons CO_2 eq/ ton CH_4	1882	-STOWA -GWP
Total direct	Tons CO_2/year		**2014**	
Indirect Anthropogenic				
CO_2 Transportation to Heerenveen	Tons CO_2/year	-39 g CO_2/ ton-km with a lorry	73	RVO.nl
CO_2 Transportation to SNB	Tons CO_2/year	-115 g CO_2/ ton-km	313	RVO.nl
CO_2 Dewatering of Sludge Heerenveen	Tons CO_2/year	-0.649 kg CO_2/kWh Country specific	425	VENM.nl, 2018
CO_2 from pre-treatment	Tons CO_2/year	-1 kg CO_2/kg COD	327	STOWA
CO_2 Electricity purchased	Tons CO_2/year	-0.649 kg CO_2/kWh Country specific	1996	VENM.nl, 2018
CO_2 from Chemicals used	Tons CO_2/year	-56.1 kg CO_2/ GJ - Iron chlorosulfate 12.3 MJ/kg - Iron sulfate 3.4 MJ/kg - Polyelectrolyte 64.45 MJ/kg	151	RVO.nl, 2015
Total indirect	Tons CO_2/year		**3285**	
Biogenic emissions of carbon				
CO_2 from aeration	Tons CO_2/year	-1.2 kg CO_2/kg COD	8511	STOWA
CO_2 from digestion (35%)	Tons CO_2/year	-685 kg CO_2/ m3	313	Bryns et al, 2013
CO_2 from CHP	Tons CO_2/year	-84.2 kg CO_2/GJ Country specific	553	RVO.nl, 2018, 2005
CO_2 from torch	Tons CO_2/year	-1.962 kgCO_2/m3 Country specific	524	RVO.nl, 2018
Total biogenic	Tons CO_2/year		**10228**	
Total GHG emissions	Tons CO_2/year		**15200**	

Chapter 4 Alternative solutions for the reduction of the carbon footprint

4.1 Introduction

Based on the Report 2018 of the United Nations Environment Programme (UNEP), there is a significant "emission gap" to achieve the Paris Agreement goals under the current operating systems. In The Netherlands, initiatives such as "Energiefabriek" and "Grondstoffenfabriek" have already started to explore alternative approaches even though the traditional concepts of biological methods are still part of many WWTPs. Additionally, the analysis of GHG emitted by the WWTP in paragraph 3.5 highlights the need for consideration of the biogenic carbon emissions (estimated 65%, paragraph 3.6) and the emissions derived from the conventional aeration process (Minx et al., 2017). According to Lu (2015), 1.57% of the global GHG emissions (49 Gt CO_2 eq) was calculated for the estimation of the degradation of the organics during wastewater treatment processes. AR5 announced the necessity of CO_2 extraction up to 90% in the second half of the century, to reach a reduction of the global temperature target. In this regard, some studies conclude at the importance of alternative approaches such as the balancing emissions by capturing the carbon and implementation of negative emission techniques (Minx et al., 2017; Fuss, 2017; Van Vuuren, 2013). Negative emission technologies (NETs), as mitigating actions for global warming, are currently available only on a theoretical level. Although these technologies, such as microbial electrolytic carbon capture (MECC), microalgae cultivation, bioenergy combined with carbon capture and storage, biochar, direct carbon capturing and others have been researched over the last few years, they have gained the public concern after the recently AR5 announcement (Fuss et al., 2014, Global CCS Institute, 2019).

For this thesis, high intervention solutions are defined as those that require total reconstruction of the plant and their application is not yet fully commercialized. The first high intervention scenario includes MECC, microalgae cultivation and biochar as a compact system of negative emission solutions for potential climate neutrality or even climate negativity in the WWTP. As climate negative WWTP can be defined the one that not only can reach climate neutral conditions but also can capture exogenous GHG emissions. Due to time limitations but also the lack of literature and empirical data on implemented systems related to negative emission methods, the analysis is based on assumptions and further examination is necessary.

Apart from the negative emissions concept which is currently not implemented in full-scale operations, many studies have recently focused on changing the conventional system of activated sludge to more sustainable energy and resource-efficient methods with low GHG emissions (Gong et al., 2014; Jin et al, 2016). Different physical, biological and chemical strategies have been proposed for alternative management. Carbon redirection technologies (see appendix 2) can remove particulate, colloidal and soluble organic matter from the system to produce sludge, usable for energy, fertilizer or other biomass products (Meerburg et al., 2015). However, apart from the analysis of the NETs, this chapter further examines the Core project found in The Netherlands which is based on physical separation of the carbons with Forward Osmosis. The selection of this project as the second high intervention scenario is based on the findings in chapter 3, where aeration process generates 60% of the total GHG emissions and also the near future changes where the electricity and thermal needs of the plant will be covered mostly with renewable energy (personal communication with members of WF). Therefore, under Core project, an alternative route is followed as presented below, with the potential of reducing drastically those emissions.

4.2 Policy implication

According to IPCC (2014), supported that even if the national and organizational measurements and policies are well determined and fully implemented by 2030 and later on, it is estimated remaining warming of 2.7 degrees Celsius by the end of the century. This means that facing global warming, mitigating measures are required. Although the European Commission initiated the EuTRACE project (2014), where European expertise assessed the potential and the risks of those alternatives, they concluded that they cannot consider NETs as a near-future climate policy plan but as a long-term strategy. In this regard, in Brussels, 4 years later (June 2018), the European Commission set a strategic long-term vision for climate-neutral economy. The aim of this strategy is not to launch new policies or to change 2030 targets, but to highlight the direction of Europe for reaching Paris Agreement objectives following UN Sustainable Developments Goals. This means that in the future, a broader set of EU policies will be affected. Finally, on the report of the annual meeting of the European gas regulatory forum (June 2019), the potential for CCS and therefore the potential of NETs was examined. Although CCSs are still in the research stage and are related to many uncertainties (financial, land use, energy use and others), estimations showed that there is a great difficulty to reach Paris Agreement targets without them (European Commission 2018; European gas regulatory forum, 2019). Water industry cannot be excluded from this mitigating plan and the biogenic emissions found in chapter 3 can show the need for consideration.

4.3 Negative Emissions Technologies

Under the negative emissions solutions it is important to clarify that there are no emissions due to the wastewater treatment processes but on the contrary, it occurs absorption of endogenous and exogenous CO_2. This means that not only climate neutrality can be reached but also climate negativity is possible to be achieved in the WWTP as analyzed below. It is essential to mention that negative emission solution are still in theoretical level and the estimation of the actual CO_2 capturing, financial investments, land use and energy demand vary based on the climate conditions and the technological decision for implementation.

4.3.1a Microbial electrolytic carbon capture (MECC)

Under the concept of Microbial Electrolytic Carbon Capture (MECC), wastewater is used as the electrolyte to assist microbial water electrolysis. In the anode chamber, biodegradable elements in the wastewater are oxidized to generate electrons, protons and CO_2, by microorganisms called electroactive bacteria (EAB). According to Wang & Ren (2013), Lu et al. (2015) and Zhu & Logan, (2014) this means that wastewater is used as an electrolyte for a microbial electrolytic generation of H2, protons at the anode and OH- at the cathode. Therefore, “The balance of OH- is based on the acidity dissolved silicate and the liberated metal ions, which generate metal hydroxide” (Erable et al., 2011; Ditzig et al., 2007). This allows the conversion of CO2 into bicarbonate (Lu et al., 2015). There are several Microbial Electrochemical Systems (MESs), which share the same principle in the anode chamber, where waste materials are oxidized and generate electrical current. Table 4 presents some of the MESs which can be applied in WWTPs, with the relative input (electron donor and acceptor) and output (product), based on a literature review conducted.

Table 7. Microbial Electrochemical systems applied in wastewater

Type of MES	Electron donor	Electron acceptor	Main product	Reference
Microbial electrochemical snorkel (AKA short-	Wastewater	Oxygen	Treated water No Electricity	Erable et al., (2011)

circuited microbial fuel cell)				
Integrated photo bioelectrochemical system (IPB)	Wastewater	Oxygen	Electricity Algal biomass	Xiao et al., (2012)
Plug flow microbial fuel cell (PF/MFC)	Wastewater Sodium acetate	Oxygen	Electricity	Karra et al., (2013)
Bio Electrochemically assisted microbial reactor (BEAMR)	Wastewater	Proton	Hydrogen	Ditzig et al., (2007)

Based on Heidrich et al. (2010), MECC has some significant advantages since does not produce toxic chlorine elements and can generate high amounts of energy current. Furthermore, the analysis conducted by Lu et al. (2015), showed that around 80-93% of the CO_2 produced by organic oxidation, but also exogenous CO_2 can be captured. Additionally, the remaining organics can be removed up to 100% via high rate H2 generation. Another essential point for MECCs is that although it is an anaerobic process it can operate in low temperatures (around 4 degrees Celsius), in contrast to anaerobic digestion, which requires high thermal energy. This means that energy efficiency of 80% can be estimated (Lu et al., 2015). Finally, the fact that the microbial electrolysis is endothermic means that it demands low voltage to operate, thus, renewable energy options such as microbial fuel cell with production of H2, reverse electro dialysis cell and photo catalysis can offer these low voltage requirements (Ditzig et al., 2007; Zhu et al., 2014; Lu et al, 2016, 2017). At this point it is crucial to clarify that MECCs are in a laboratory stage and further research is required to decrease the costs, find alternative low-value minerals, remove nutrients and most importantly to reach the water quality required under the European and national regulations.

4.3.1b Estimation for WWTP Leeuwarden

Based on paragraph 3.6.2, biogenic emissions due to aeration process were calculated 8511 tons CO_2/year. The estimation of 4.3.2a shows around 85-93% reduction of the total CO_2. This means that the current 8511 tons CO_2 can be eliminated to 595-1700 tons CO_2/year and the remaining can be converted up to 100% into H2. This means that at least 60% of the total current emissions, derived from aeration process, can be removed from the carbon footprint of WF. Also, through MECC an estimation of 80% less sludge production was found. This leads to the assumption that not only the energy demands and the cost of sludge management will be reduced, but also the annual sludge disposal of the WWTP will be decreased from 55995 to 11199 tons.

4.3.2a Microalgae cultivation

Additional to the implementation of MECCs, microalgae cultivation can be the second stage of the first high intervention solutions, where CO_2 is captured during autotrophic growth, biomass energy source is provided and nutrients (N, P) can be removed (Arashiro, 2016). Also, microalgae can provide a large variety of bio-products and has gained attention as a renewable source for biofuel production. Figure 7, presents the bio-products that can be produced from microalgae cultivation. Some of the most well-known phototrophic systems are the high rate algal ponds, photo-bioreactor, and stirred tank reactors (Shoener et al., 2014). According to Shchegolkova (2018), columnar photo-bioreactors (PBR) provides high efficiency of phosphorus and nitrogen removal up to 90%. However, the capital costs of PBR is much higher than the implementation of algal ponds (Barros et al., 2015). Moreover, Hu et al. (2017), supported that the key for small footprint and high productivity of micro-algal treatments is the usage of enriched and suspended bacterial cultures that reach high performance (Su et al, 2012). Shoener et al. (2014) and Ptacnik et al. (2008) agreed that mixed cultures of microalgae and bacteria achieve high nutrient recovery from wastewater up to 99%. It was found that autotrophic cultures can fix 1.8-2.4 kg CO_2/ kg biomass grown (Li et al., 2017; Leow et al., 2015). Table below summarizes some of the microalgae species with the relative CO_2 absorption, the necessary temperature and the biomass productivity based on conducted literature review which can offer promising results in terms of CO_2 capturing and biomass production. Finally, it was found that the combination of MECC and microalgae cultivation can provide higher carbon capture and utilization. MECC firstly exploits the influent organic carbon and further, microalgae can polish COD to reach discharge standards by providing sustainable biomass (Lu et al., 2018).

Table 8. Microalgae species for CO_2 sequestration (Razzak et al., 2019; Wang et al., 2008)

Microalgae species	**CO_2 capture (%)**	**Temperature (C)**	**Biomass production(g/L d)**
Chlorococcum littorale	40	30	Not available
Chlorella kessleri	18	30	0.087
Chlorella vulgaris	15 (Air)	25	0.040
Scenedesmus obliquus	18	300	14

4.3.2b Estimation for WWTP Leeuwarden

As mentioned in paragraph 4.3.1, MECC can capture up to 85% of CO_2 and the remaining can be converted into H2. In this case, based on table 6, 15-40% of exogenous CO_2 can be captured additionally. Further, microalgae cultivation adds more value in the WWTP by offering biomass production. Based on the potential capturing by the bacterial cultures mentioned above with 1.8-2.4 kg CO_2/ kg biomass grown, if the WWTP produce for example, 50000 tons biomass per year, this means that it fixes around 100.000 tons CO_2/year. In this study the estimation of the potential biomass generation and the exact GHG capturing are excluded due to the time frame and the word limit but also the difficulty to estimate under actual conditions. It is important to mention that although microalgae cultivation can be a sustainable solution for nutrients removal, absorption of CO_2 and conversion of it into biomass, its performance is not predictable and large land areas are required. Finally, harvesting biomass demands high energy and maintenance costs and further research is required to improve organics removal and reaching a stable performance of nitrogen, phosphorus permit requirement with an almost zeroing footprint (Lu et al., 2015).

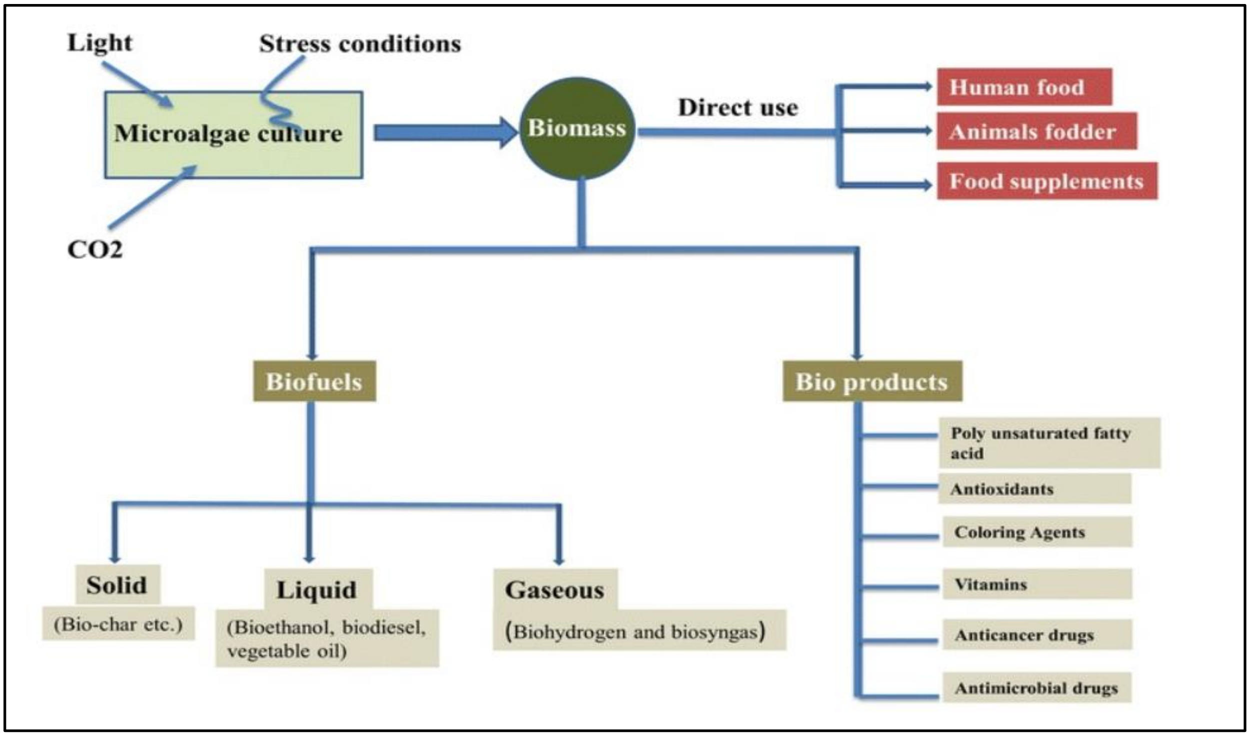

Figure 8. Microalgae convert CO2 by using light and under stressed conditions, into valuable biomass which can be used directly for human food, animal fodder and food supplements. Further, biomass can be converted into biofuels (solid, liquid, gaseous), or into bio-products (fatty acids, antioxidants, vitamins, drugs).

4.3.3a Biochar

For the purpose of this thesis, the option of biochar production as the solid biofuel output is chosen to be analyzed. Based on Qambrani et al. (2017), pyrolysis is one of the most encouraging technologies for conversion of biomass into high-value source such as biochar. Torrefaction or slow pyrolysis can generate high yield biochar. The efficiency of the production is deeply based on pyrolysis parameters such as temperature, heating rate, reactor conditions, type and composition of the feedstock, etc. According to Lu et al., 2018 some wastewater sludge, microalgae and wetland plants have already exploited the biochar opportunities and shown that the usage of biochar as a soil amendment, augments the fertility and improves nutrients and water reservation (Qambani et al., 2017; Lu et al., 2018). Some further advantages of biochar are the elimination of pathogens and improved soil quality and fertility, but also a decrease of heavy metals and the adsorption of pesticides. The suitability of biochar as an option relies on the short-term photosynthesis-mediated carbon cycle to a long term carbon reservoir in the soil. However, these advantages are highly dependent on the properties of the biochar and soil, the local climate and other factors (Xiao et al., 2018, Huggins et al, 2016; Lu et al., 2018). Making a comparison with the current system where the dry sludge is incinerated and considered waste, the option of carbonizing the byproducts into biochar production may offer environmental and financial benefits (Mendez.et al., 2012). Results from the study of Smith et al (2016), indicate that soil carbon sequestration and biochar have useful negative emission potential (0.7-0.9 Gt CO_2/year) which can potentially have a lower impact on land, water use, nutrients, albedo, energy requirement and cost. Thus, it has fewer disadvantages than many other negative emissions technologies. Finally, biochar could be considered as an adaptive measure since it can be applied under current operating systems (Smith et al., 2016).

4.3.3b Estimation for WWTP Leeuwarden

In accordance with Hossain et al. (2011) and Allashimi et al. (2017) 100 tons of dry sewage sludge per day can produce 65 tons of biochar, assuming a yield of 65% and around 21 kt CO_2 eq can be captured per year based on a GHG emission factor of 0.9 kg CO_2eq per kg biochar. In the scenario that only biochar production is selected as a mitigating solution for climate neutrality, where currently the WWTP in Leeuwarden produces 55.995 tons of wet sludge annually. Based on organizational document, it was found that 3% of this amount is dry sludge. This means that 983 tons of biochar can be generated if biochar technology will be implemented as a future plan.

The figure below shows the compact system suggested as a high intervention solution for the WWTP in Leeuwarden with the combination of MECC, microalgae cultivation and biochar production.

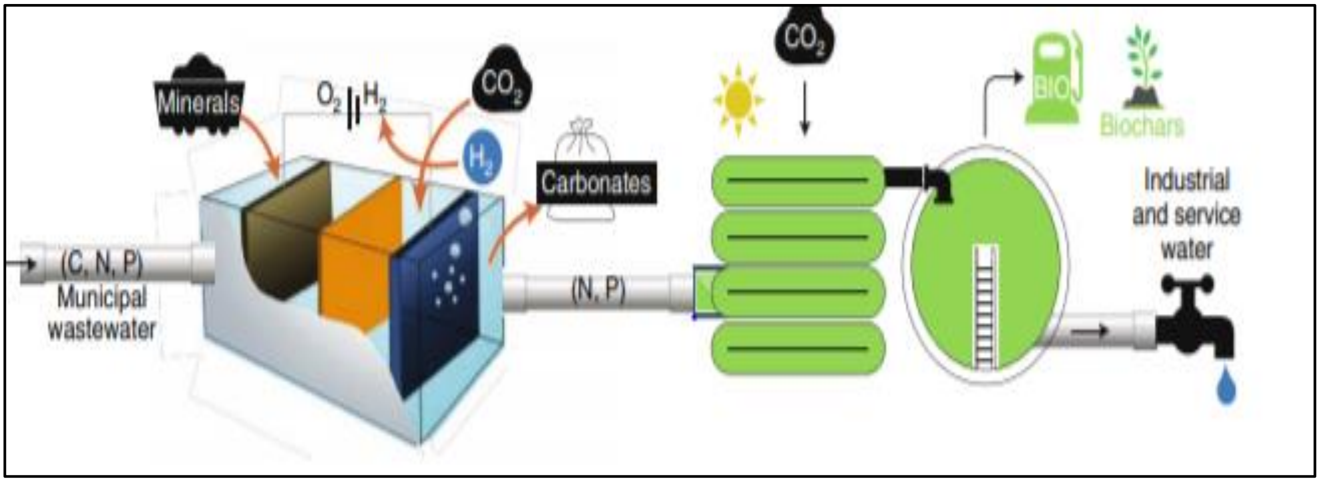

Figure 9*, Compact system for the WWTP with negative emission solutions (Lu et al., 2018)*.

In Figure 8 a compact system is shown of a combination of MECC with microalgae and biochar. In the first stage municipal wastewater, as input enters the system where MECC is applied, minerals are added, 85-93% of CO_2 is absorbed, H2 is generated and carbonates are produced. In the second stage, microalgae cultivation with the assistance of light, 15-40% of CO_2 is absorbed and biomass is generated. Finally, biomass is upgraded into solid biofuel. Biochar and industrial service water are the output of the operation with the absorption of 0.9 kg CO_2eq/ kg biochar.

4.4 Core Project

Based on the analysis conducted by TKI Water technology with the operation of a first pilot at the Wehl sewage treatment plant of the Rijn and IJssel water board (kwrwater.nl 2018), the “Concentrate, Recover and Reuse (CORE)” concept was invented, where the municipal wastewater is separated by Forward Osmosis (FO). Therefore, a high concentrate of organics and clean water are offered. The clean water can also be updated even to drinking water, with an estimated smaller footprint than conventional systems. The application of direct membrane filtration on raw wastewater is interesting because the high concentration of the components make energy and nutrients recovery possible (Bluetec, 2017). The treatment steps of the Core project which are taken into consideration at this thesis are:

1) Pretreatment for the removal of particulate matter
2) Forward Osmosis for the concentration of the wastewater and Reverse osmosis for the generation of clean effluent
3) Anaerobic digestion for biogas production
4) Final treatment of the concentrate with the VUNA technology, which uses activated carbon, adsorption and distiller to generate liquid fertilizer but also removes remained pathogens and micro-pollutants.

4.4.1a Pre-treatment

The pretreatment stage is usually required before the wastewater enters the FO installation and is dependent on the membrane configuration type in the FO unit. It is a crucial stage for the total operation and performance of the WWTPs since its high performance can assist on an early high concentration of organics and thus, fewer operation processes are required for any primary treatment stage chosen. The Core project includes sieve drum screening for pretreatment processes, which can remove mesh size up to 50μm with a COD removal of 35% and 50% of suspended solids, as also proposed in the Road Map for 2030 by STOWA (Bluetec, 2017; STOWA, 2010). The final disposal of the sieved fraction in the pretreatment can be used directly for digestion in contrast to the current system where disposals are incinerated. Based on literature review, it was found that some other physical primary filtration technologies are in a high level of readiness and some of them are the compressed media filtration Fuzzy Filter (Schreiber Corporation, AL), the Clear Cove Systems with a physical clarification and filtration of wastewater, and the Salsnes Filter from Trojan technology, which can alternatively be used with similar COD removal efficiencies (Sancho et al., 2019).

4.4.1b Estimation for WWTP Leeuwarden

Considering the information found and taking into consideration that only 5% of the total COD is currently captured in the WWTP in Leeuwarden it can be said that potentially 30% more COD can be captured in the pre-treatment stage. This means that if the current COD is 7446 tons/year and the COD removal is 35%, then 3127 tons of valuable COD can be captured and utilized directly in anaerobic digestion (paragraph 4.4.4.1), instead of 327 tons COD/year which currently captured and incinerated. Further, the early capturing of the organics will lead to less energy demand and operation treatments at the next stages.

4.4.2a Forward Osmosis

Forward osmosis (FO), has been shown to concentrate both nutrients and suspended solids in wastewater and is selected as a physical primary stage of the solution suggested (Cath, Childress, and Elimelech 2006; Holloway et al. 2007). Under this concept, the organic matter is not degraded but is concentrated in a separated tank. Therefore, CO2 is not emitted but is concentrated and utilized. The process of osmosis is a physical treatment process which transports water across a semipermeable membrane in order to balance the solute concentration. FO membranes facilitate the flux of water (solvent) while blocking the passage of most suspended and dissolved particles (solutes). Osmotic pressure is imposed by the concentrated dissolved solutes from the liquid. Further, water in the feed solution, which has lower osmotic pressure, is pulled through the membrane into the draw solution with a higher osmotic pressure. Therefore, it can be said that the membrane is used as a physical barrier which prevents the entrance of most salts and suspended solids (Zhao et al., 2012). According to KWR, one of the most essential factors in the application of FO is the well-selected process for reconcentration of the draw solution after the diluted FO process. Also, reconcentration of the draw solute can occur with the usage of other dense, non-porous, selectively permeable membranes (Sancho et al., 2019). Based on KWR (Bluetec,2017) the most promising is the thin film composite

(TFC) membranes, which are characterized as more water permeable and with low solute permeability values. In contrast with the conventional pressure-driven membrane processes, they demand low energy inputs, have low fouling tendency, have minimal pretreatment requirements, reduce cake layer formation and finally, have a low-pressure operation which simplifies the design and the equipment used. Treatment of municipal wastewater with FO membranes is an innovative concept that could achieve advanced treatment standards with less GHG emission, low energy use (0.31 kWh/m3) and less fouling problems than conventional membrane technologies, reaching high quality of treated water, by concentrating up to 99.8% of the main organics. This means that the water can be reused as industrial water for irrigation and the concentrated wastewater can be fully utilized by anaerobic digestion (Buckwalter, 2017; VPWNN FWW, 2017). Despite the fact that FO can be characterized as a simple process, mass transport through FO membranes, concentration polarization, membrane fouling, reverse diffusion are complicated issues and are based on a variety of parameters such as type of membrane, structure, temperature, composition of wastewater, hydraulics, and others (Sancho et al, 2019). The essential point of FO technology is that there are no GHG emissions associated since the organics are concentrated and fully utilized further. However, there are not many available models for FO mass transport and membrane modules, especially for WWTPs, implemented and further research is required. (Verstraete et al., 2009). In the figure below, the FO process with the combination of the draw solute recovery system is shown.

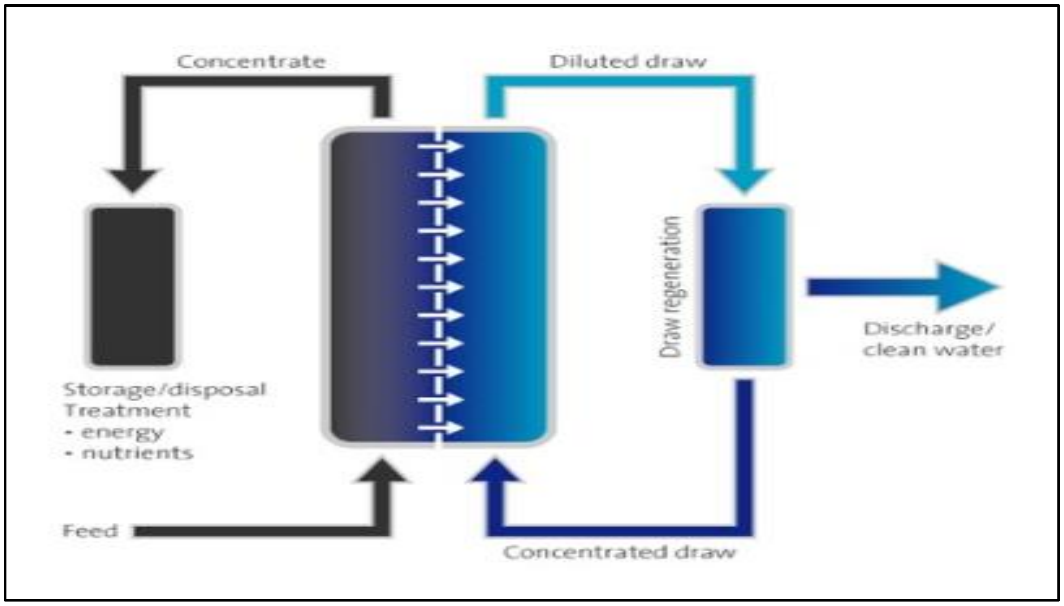

Figure 10. FO process with the draw solute recovery system, where the wastewater (feed) enters the system, the organics are concentrated in the left tank and through FO treated water is discharged from the right tank, after the draw regeneration.

4.4.2b Estimation for WWTP Leeuwarden

As mentioned in paragraph 4.4.1b 35% of the total 7446 tons of COD is captured in pre-treatment. This means that 4319 tons of COD remains in the wastewater and enters the FO system. Based on the aforementioned finding, 99.8% is captured by FO and further is utilized by anaerobic digestion. This means that 4310 tons of COD are not oxidized but fully used for biofuel production in comparison with the current system where 7000 tons of COD annually is oxidized and emitted in the form of 8511 tons of CO_2 into the atmosphere.

4.4.3a Draw Solute Recovery

The concentrate on the permeate membrane’s side is the leading force for FO process. It was found that NaCl is mostly used as a draw solute because it is highly soluble, has low cost and high osmotic potential. In the case of Core, the drawing recovery can produce reusable water, and even drinkable, with Reverse Osmosis in combination with energy recovery. However, considerable is the energy requirements of this stage.

4.4.3b Estimation for WWTP Leeuwarden

Based on the Core project, 2.13 kWh/m3 of influent are required in order to provide clean water. This means that the FO with RO stage demands 143000 GJ/ year only for the provision of treated water. This estimation is 10 times higher than the current energy requirements of the biological treatment (paragraph 2.3). However, RO can offer drinking water and the energy requirements can be covered by the on-site biogas production from anaerobic treatment. This means that there is a potential for the water board to provide apart from the wastewater treatment facilities, also drinking water, by avoiding the operation of two different units and thus less energy will be required (Nexus of Water boards with fresh water organizations). In this case, public acceptance, financial interests and relative governmental support has to be further analyzed.

4.4.4 Concentrate treatment

Apart from the provision of clean water, the FO system generates also concentrate (reject) which volume is highly dependent on the nature of the wastewater and the recovery rate of the FO process, but in this pilot application it was estimated 90%. Several technologies are applicable for the recovery of valuable resources and removal of a polluting component such as anaerobic treatment, nutrient removal and final treatment for the removal of micro-pollutants with crystallization, anaerobic digestion and others (Bluetec, 2017). STOWA also presented in its Road map report (2014), other techniques such as biochemical dewatering with enzymatic hydrolysis, thermal hydrolysis and biological techniques, organic mass reduction techniques with mesophilic or thermophilic digestion and other final treatment such as gasification and pyrolysis. However, in this thesis, anaerobic digestion with high rated anaerobic reactors is selected due to the 50 years of experience with digestion on the WWTP of Leeuwarden (personal communication).

4.4.4.1a Anaerobic digestion

Under the Core project, anaerobic digestion generates biogas from remaining organics with high rate anaerobic reactors which have COD loading rates up to 15 kg COD/m3/day and removal efficiency of 80%. Based on the final report of VPW FWW is also found that the COD conversion can be up to 75% and the boiler efficiency is 90%. Based on the Core analysis, the biogas production with high rated anaerobic reactors can cover the high energy demands of the distiller as described below in paragraph 4.4.6.

4.4.4.1b Estimation for WWTP Leeuwarden

Based on paragraph 4.4.2b, 4310 tons of COD is captured in FO stage and 3136 tons in pre-treatment. Anaerobic digestion can convert 75% of COD into biofuel. This in case of Leeuwarden means that the remaining COD from pre-treatment (65%), is fully concentrated in FO process, and further is utilized in the anaerobic digestion. This means that biogenic emissions are not involved in the FO stage, but in the anaerobic treatment 75% of the total COD is converting into valuable biofuel, by leaving a 25% of CO2 emissions from the anaerobic digestion.

4.4.4.2 Final removal of organic micro-pollutants

The decision of the final treatment method is highly based on the actual composition of the concentrate and the local discharge. At this moment an additional treatment is not required by national law. However it is expected that within 10 to 20 years also micro-pollutant removal will be necessary (personal communication). Therefore, in the future additional treatment with activated carbon filtration, ozonation, and other alternatives may be required (See appendix 2).

4.4.5 VUNA Technology

As shown in figure 10, fertilizer is one of the valuable options for biomass harvesting. Under the Core project, VUNA technology which was developed at EAWAG, in Switzerland, is incorporated into the compact Core system. The first stage of Vuna technology is the nitrification process in a packed bed reactor, where the liquid is converted into NO3 and heterotrophic bacteria remove the remaining organic substances. The COD conversion is 30% while the energy consumption is estimated at around 0.91 kWh/m3. Further, through the distillation, the cake volume is eliminated and creates a liquid fertilizer as a final product which is free of pathogens and the energy demands are 50 kWh/m3 (thermal energy). Based on literature review but also based on the Core project, distillers with vapor compression used have 90% energy recovery (paragraph 4.4.6). However, the quality of the liquid fertilizers is based on many factors such as the quality of the concentrate, growing conditions and maintenance but it seems that VUNA fertilizer can perform with N=6.3%, P=1% and COD=3.3% (VPW FWW Final report, 2017). This means that the fertilizer can be comparable with commercial ones, providing financial benefits to WF (Sanadi et al., 2019). It is significant to mention that VUNA technology uses nitrification process. This means that the analysis and the estimation of the N_2O emissions due to this process have to be calculated and to be considered in future research.

4.5 Energy requirements

Based on the paragraphs 4.4-4.45 and the FWW analysis report, it was found that the suggested system is able to operate under energy neutral or even energy negative conditions. The high energy demands of the distiller can be fully covered by the biogas production under anaerobic digestion. Further, since the wastewater influent is pre-concentrated, the size of the bioreactor is considerably smaller. This influences the footprint of the plant but also can contribute to lower energy requirements. More specifically, the energy balance of the Core project shows that the energy consumption is between -37 to 7 MJ/PE. This means that in case of Leeuwarden is -6751 GJ/PE to 1277 GJ/PE, which leads to the conclusion that Core project also has the potential to be an energy provider.

However, the capacity of the existing pilot installation is 0.2 m3/hour and its use is supplementary to investigate FO itself, anaerobic treatment, nutrient recovery and how it can be scaled up. Currently the WWTP of Leeuwarden operates at a maximum of 8000 m3/hour. This means that the potential for higher capacity has to be researched in order to be applicable under the current wastewater treatment needs in case of WF.

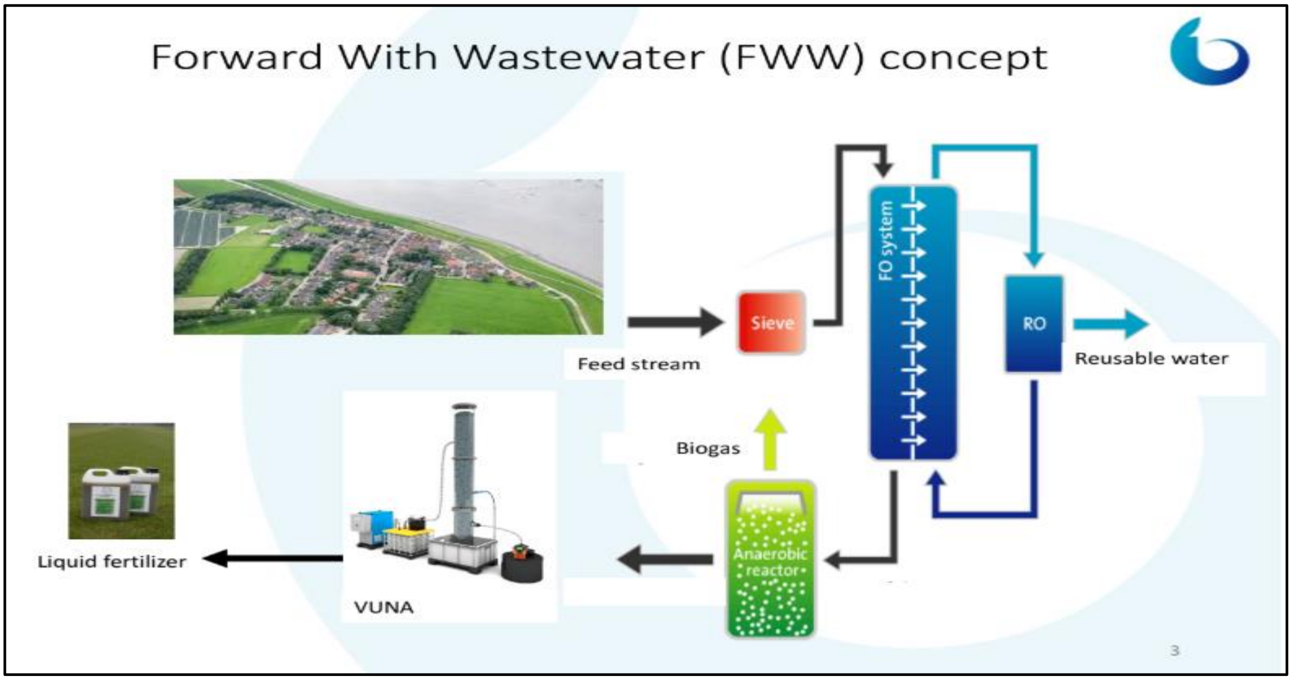

Figure 11. Core project with sieving as pre-treatment, FO and RO as primary treatment for reusable drinking water provision, anaerobic digestion with high rated anaerobic reactors which provides biogas. VUNA technology finally is applied for the production of liquid fertilizer.

Based on the aforementioned paragraph 4.2-4.4, the table below summarizes the main advantages and disadvantages identified during the literature review.

Table 9. Advantages and disadvantages of the suggested alternative solutions

Intervention solution	**Advantages**	**Disadvantages**	**Reference**
MECC	-High CO_2 capture and utilization (85-93%) -100% H_2 generation from remaining -Low energy demand -80% reduction on energy efficiency - Organic removal with low sludge	-A low value of carbonates as a byproduct -High capital cost -Limited nutrient removal -Requires large scale implementation -Use of minerals -Theoretical Level	-Lu et al., 2018 -Erable et al., 2017 -Xiao et al., 2018
Microalgae cultivation	-High carbon capture and utilization (exogenous and endogenous) 15-40% -Biomass generation -High nutrient removal	-Uncertain performance and quality -Large land area required -High energy and cost for biomass harvesting -Limited organic removal	-Lu et al, 2018 -Arashiro, 2016 -Hu et al., 2015 -Li et al., 2017
Biochar	-Eliminates pathogens -Improves quality, fertility, nutrients, soil -Smaller footprint than conventional systems -Produces of energy -Long term carbon storage in soil	-CH_4 and N_2O emissions -Range of energy generation potentials - Additional cost for production	-Lu et al., 2018 -Fuss, 2017 -Minx et al., 2017 -Smith et al., 2016
Core -FO -RO -Anaerobic digestion -VUNA	-Low fouling tendency and minimal pretreatment requirements -Production of high quality water, biogas and liquid fertilizer -Reduce cake layer formation -A low-pressure operation which simplifies the design and the equipment used -Energy neutrality and nutrients recovery	-Is still on pilot scale. - It requires a scale-up for treating all the wastewater of Leeuwarden -Public acceptance -Lack of policy and regulations	-Personal communication - FWW, KWR, 2018

4.6 Conclusion of the chapter

Based on the Report 2018 of the United Nations Environment Programme (UNEP), there is a significant "emission gap" to achieve the Paris Agreement goals under the current operating systems. Therefore, in this chapter are investigated the technological options that could provide climate neutral conditions and thus the third sub question, "*What technological options are feasible for climate neutrality in the WWTP?*" can be answered. As high intervention solutions are defined those that require total reconstruction of the plant and their application is not yet fully commercialized. The first high intervention scenario includes MECC, microalgae cultivation and biochar as a compact system of negative emission solutions for potential climate neutrality or even climate negativity in the WWTP. As climate negative WWTP can be defined the one that not only can reach climate neutral conditions but can also capture exogenous GHG emissions.

Apart from the analysis of the NETs, this chapter further examines the Core project found in The Netherlands which is based on physical separation of the carbons with Forward Osmosis. Table 7 below summarizes the findings of paragraphs 4.2, 4.3 and 4.4 regarding the energy demands, biogenic emissions and the stage of implementation of the current system in comparison with the suggested NETs and the Core project.

As presented, the current energy demand of the WWTP in Leeuwarden system is 17000 GJ/year (paragraph 2.4). This amount is essentially high in comparison with the Core project which can operate under energy-neutral/negative conditions. This means that the plant can provide theoretically, 6751 GJ/year based on the PE of Leeuwarden. Further, based on literature review was found that MECC technology requires 80% less energy than the current operating systems. However, the precise estimation of the energy demand for NETs is based on many factors such as climate conditions, the quality of influent, type of culture etc. are excluded from this study.

Regarding the GHG emissions associated with the current system, was found that 64% of the total emissions are biogenic (9823 tons CO_2/year). The NETs found to be an interesting alternative for reaching climate neutrality since they can offer negative percentages of GHG emissions by capturing endogenous but also exogenous CO_2. The Core project is associated with around 1000 tons CO_2/year due to anaerobic digestion, where CO_2 is emitted from the biogas combustion and further research is required to eliminate to zero those biogenic emissions.

Table 10. Comparison of the current system with NETs and Core in terms of energy demands, GHG emissions and the stage of the implementation.

	Current System	**MECC**	**Microalgae**	**Biochar**	**Core**
Energy Demands	17000 GJ/year	3000 GJ	Not available	Not available	-6751 GJ/year to 1277 GJ/year
Biogenic emissions	9823 tons CO_2/year	0/-	0/-	0/-	1000 tons CO_2/year
Stage of implementation	High experience	Theoretical level	Some experience	Some experience	Pilot

Chapter 5 Findings

5.1 Conclusion

The results obtained in this research have shown that the WWTP can be associated with high GHG emissions and energy demand. Although internally, the organization has already seen the potential for energy efficiency, not much has been done to evaluate the total direct, indirect and biogenic GHG emissions of the plant. After the announcement of AR5 regarding the failure of the target concerning the reduction of the global temperature, many technologies have been arranged to utilize efficiently and sustainably the unused provision of carbon associated with such processes and find alternative mitigating solutions. The use of these technologies will play a crucial role in the future, due to the financial, environmental and energy constraints normally associated with conventional WWTPs.

WF aims to reach climate neutrality by 2030. In this regard, the analysis of the current GHG emissions and the examination of possible mitigating solutions are examined. Therefore, an attempt was made to formulate an answer to the following research question: *"What is climate neutral wastewater treatment and what are technological feasible options to achieve climate neutrality in the WWTP in Leeuwarden?"*

To answer this research question, the current state of the art of the WWTP was firstly investigated and answered by the first sub-question. This examination contributes not only to have a better understanding of the water treatment systems but also constitutes the first step in order to be able to examine the GHG released directly, indirectly and biogenically in the WWTP. Therefore, the first sub-question, "*What is the current technological state of the art of the WWTP in Leeuwarden?"* can be answered.

Through the wastewater treatment processes municipal and industrial wastewater return to the environment with adequate quality. These processes traditionally are divided into primary treatment (pre-treatment), secondary treatment (normally biological treatment), post and tertiary treatment stages. In the case of Leeuwarden, sludge treatment and energy recovery are part of the plant as well. In the first stage of pre-treatment, mechanical screening takes place which is responsible for the removal of 5% of the total COD/year.

Further, the secondary (biological) treatment starts. The sewage water ends up in the 6 denitrification tanks, where the water from the aeration tanks is recycled. The WWTP in Leeuwarden uses the "Carousel" type aeration tanks for aeration. After passing the denitrification tank, the sewage water is led to the aeration circuits. Oxygen is introduced into the water-sludge mixture through the surface aerators. Thus, the contamination from the bacteria is removed (oxidized). After the secondary treatment, the post treatment follows. The cleaned sludge-water mixture enters the settling tanks (clarifiers) after the aeration process. The type of clarifier used in the plant is Circular Center Feed. Additionally, the sludge treatment is the next stage of the wastewater management of the WWTP in Leeuwarden. The sludge is mixed with a polymer and then spread over a sieve cloth. The type of sludge thickeners that are used is Bellmer Turbodrain TDC-3. The sludge stream is introduced into the fermentation process (digestion) while the water returns to the aeration tanks. By digestion process methane gas is emmited, which is primarily used for heating the fermentation tank. The biogas that is created supplies the combined heat and power plants (CHP), which produce electricity for the WWTP, and residual heat for heating purposes. This stage is considered as the energy recovery stage in the WWTP. The type of CHP used is Mann E 2542. Additionally, the methane gas which is generated is stored in a gas container. The sludge is periodically transported by lorry to the central sludge dewatering installation of WF in the city of Heerenveen.

In this stage, it is important to mention that, although this thesis is focused on the analysis of the GHG emissions in order to reach climate neutrality, the examination of the energy use in the wastewater treatment plant is crucial since the energy usage is a significant contributor to the indirect GHG of the plant. The energy analysis conducted, showed that the total electricity needs are 17,638 GJ/year, where 62% is purchased from an electricity company (11,070 GJ/year) and the remaining 38% of its energy needs are generated by the plant through CHP facilities (6,568 GJ). It is also estimated that the motors are capable of generating around 30% of electricity and 70% of heat. This means that 1,979 GJ /year electricity and 4,598 GJ/year heat are generated to cover the energy needs of the plant. The heat generated by the CHP facilities is divided into 55% for heating purposes at the sludge treatment stage (2,529 GJ/year), 30% supplying the neighboring elderly house (Greunshiem), the (1,379 GJ/year) and 15% is considered as heat loss (690 GJ/year).

The electricity is used mostly for the aeration processes, pumping, clarifiers and the digesters as can be seen in the figure below. An essential point is that the aeration process consumes around 70% of the total electricity needs (12,308 GJ/year), while the remaining 30% is covered by the clarifiers, digesters and pumping processes. The annual influent that enters the plant is around 16 million m3 and the total sludge disposal is 55,598 tones/year.

The second sub-question, *"What is the current GHG emissions associated with the WWTP?"* is analyzed and answered in chapter 3. Subsequently, based on literature review and available data provided by the organization, quantification and qualification of GHG emission was done and was related to specific steps inside the WWTP. Although few challenges appeared during this study, basically caused by unclear definitions given by governmental and organization levels, some boundaries and categorization of GHG emission was still possible and were included in this study. In the end, this thesis could present the examination and calculation of direct, indirect anthropogenic and biogenic emissions in the WWTP of the city of Leeuwarden.

The obtained results have shown that total direct emissions (2.014 tons CO_2 eq/year) are associated with N_2O from nitrification/ denitrification processes (133 tons CO_2 eq/year, 7%) and CH_4 from sludge management and disposal (1.882 tons CO_2 eq/year, 93%). Indirect emissions were also calculated and it was found out to comprise a total of 3284 tons CO_2/year. In this fraction, electricity purchasing is responsible for the highest percentage of (1.996 tons CO_2/year, 61%). Dewatering of sludge in Heerenveen and the transportation of sludge to SNB follow with 425 and 313 tonnes CO_2/year. Incineration of the sludge from the pre-treatment stage also is an essential contribution.

Biogenic emissions are currently not included in the carbon footprint of organizations and industries. However, an effort was made to calculate such emissions. It was found that it corresponds to 65% of the total emissions of the WWTP (10228 tons CO_2/year). 86% of it is emitted in the aeration process, 3% in the digestion phase (where 35% of biogas is CO_2), 6% from CHP facilities and 5% from the usage of torch. These calculations are essential as the potential of this amount of the carbon is considerable.

This analysis confirms the need for mitigation measures and utilization of biogenic emissions associated with the wastewater as announced by AR5. This also clarifies the need for drastic actions where CO_2 could be extracted and reused. In the fourth chapter, the sub-question, *"What technological options are feasible for climate neutrality in the WWTP?*" is analyzed and answered. Therefore, firstly a high intervention solution is presented which can reduce or (re)utilize biogenic emissions, i.e. the so-called negative emission technologies (NETs), were investigated. In this regard, the application of MECC in combination with microalgae cultivation and biochar was analyzed as a promising NETs compact solution. The first solutions suggested can constitute a compact system but also a separate installation of each of the three different components of the system is a plausible and possible option. For example, as mentioned, biochar can be generated even under activated sludge systems, given the opportunity of a mild transition.

At this point, it is crucial to clarify that MECCs are in a laboratory stage and further research is required to decrease the costs, find alternative low-value minerals, remove nutrients and most importantly to reach the water quality required under the European and national regulations. In addition to the biophysical and economic limits to negative emission technologies considered above, social, educational and institutional barriers, such as public acceptance and safety concerns about new technologies and related deployment policies, which could limit the implementation phase. Nevertheless, NETs are estimated to be able not only to provide climate neutrality but climate negativity since exogenous CO_2 can be captured as well.

Next to NETs, the CORE technology was investigated for its GHG reduction potential. The CORE technology is based on forward osmose (FO) and is characterized as a promising physical treatment solution. The main advantages of the Core project is that can remove micro-pollutants, provide high quality effluent, recover nutrients and finally reach energy neutrality. More specifically, taking into consideration that the quality of the effluent is the most important aspect of sustainability in the WWTPs, in the case of the Core, the pollutants, including micro-pollutants, can be retained by the membranes. This means that there is no need for post treatment while the generated permeate is highly qualified and suitable for reuse. Furthermore, the concentrate (sludge cake) produced by membrane technologies is converted to liquid fertilizer. In contrast with the current system where nutrients lose their value during the treatment processes, in the Core these nutrients are recovered as are included in the fertilizer. Finally and most importantly, Core project is highly discharged by GHG emissions and is able to provide high quality drinking water. In this case, public acceptance, organizational collaboration and relative governmental support have to be further analyzed. Also based on the Core analysis, a sustainable operation also requires renewable energy production on-site and further research for higher capacity since currently is 0.2 m3/hour, which is 1600% lower needs in comparison with the WWTP in Leeuwarden.

To sum up, climate neutrality can be reached in the WWTP in Leeuwarden if alternative mitigating actions such as NETs and other physical, biological options such as the Core project could be implemented. Many water boards have already explored and enlarged the potential of carbon capture and its utilization for further use as energy, raw materials and fertilizers. WF is already researching some circular economy initiatives such as recovery of cellulose, producing bioplastics and struvite which also act in the CO_2 footprint reduction direction. However, it is recommended that more attention has to be brought on avoiding biogenic CO_2 emissions and/or on capturing and reutilizing this fraction. The comparison of the current system with the NETs and Core project from paragraph 4.6 shows interesting results, especially from the Core project. It was found that not only climate neutrality can be reached but also energy neutrality or even negativity is possible. Although NETs are still in theoretical level, it is estimated to have negative emissions since endogenous and exogenous CO_2 can be captured.

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Appendix 1

Workshop for Climate Neutrality (1/72019)

Introduction of the Topic

The thesis topic examines the climate neutrality of the wastewater treatment plant in Leeuwarden by 2030, as it is presented in the Climate Agenda of the organization. This workshop (be part of the thesis as one the research method) aims to make participants rethink the whole wastewater treatment system considering the core issue of the elimination of the greenhouse gas emissions to zero, by tackling the capturing of carbon and its utilization. Further, it is expected to be proposed technologies which enhance capturing the carbon and to analyze the advantages and disadvantages of each option.

Climate neutrality approach

The selection of the thesis topic is based on the fact that great progress has been made to increase energy efficiency and recover renewable energy from the wastewater by using technologies such as anaerobic digestion. However, these methods, which are considered as **adaptive measures,** only can reduce fossil fuel consumption and its associated carbon emissions, whereas few have looked at the additional possibility of using wastewater treatment for active and direct CO_2 capturing and utilization. Regarding the quantity of wastewater generated each year and its positive correlation with population and industrial activities, there is a significant potential for contribution from the wastewater treatment to meet Paris agreement, national and organizational goals. Carbon Capturing and Utilization (CCU), which is a **mitigating approach**, can occur within existing wastewater infrastructure, without the need for additional land or transportation. Thus, CCU may transform the carbon-emitting and energy-intensive WWTP into integrated water resource recovery facilities which recover energy, nutrients, water and valuable carbon products with economic, environmental and social benefits.

Comments regarding the analysis of current GHG emissions of WWTP in Leeuwarden (based on the pie chart)

-Methane emissions are much higher than nitrous oxide.

-Nitrous oxide emissions are low due to the good operation of the WWTP.

-The estimation of N2O is based on the general number/ STOWA (population equivalent/emission factor).

-The use of chemicals is considerable.

-It was made clear that what is considered until now as emissions are the direct and not the indirect emissions, which makes more important the shift to a mitigating approach (capturing the carbon in the very early stage of the treatment processes).

Chemical use									
Polymer 50% actief	11.96	ton PE/yr	770822	MJ			43	tonCO_2/yr	
Iron dosing	45.6	ton $FeSO_4$	155040	MJ			9	tonCO_2/y	D
	143	ton FeClS(	1758900	MJ			99	tonCO_2/yr	
CO_2									II
Electricity	3,075,000	kWh	11,070,000	MJ	11,070	GJ	1,996	ton CO_2/yr	
Biogas in CHP	1,061,154	m3/yr							
Biogas	1,824,580	kWh	6,568,488	MJ	6,568	GJ	553	ton CO_2/yr	
Biogas torch	155392	Nm3/yr							E
	267186	kWh	961868	MJ	961.868	GJ	524	ton CO_2/yr	
Biogas delivery to Fier and Wetsu	73,676	Nm3/yr					(directly from m3)		
Total energy use					17,638	GJ		ton CO_2/yr	
CO_2 EF primary energy	0.649	kgCO_2/kWh							
N_2O	EF =	0.05%		0.3184	ton N_2O-N/yr				
	kjN	39.6	mgN/l	0.5004	ton N_2O/yr		133	ton CO_2/yr	
	Flow	16082265	m3/yr						
	GWP	265	tonCO_2/ton N_2O						
	N_2O-N	1.57	N_2O						
CH_4	EF=	113	kgCH_4/day/100.000 PE						
	Flow	44061	m3/day						
	Population Eq.	182,484	PE in 2018						
	CH_4 emission	75	ton CH_4/yr				1,882	ton CO_2/yr	
	GWP	25	ton CO_2 eq/ton CH_4						

Transport of sludge to Heerenveen		55400	ton /yr				**73**
	EF	41	gCO_2/tonkm	with ship			
	Volume ship	1000	m^3				
	trips	55.4					
	km to Heerenvee	32					
	total	1773	km/yr				
	tonkm	1772800	tonkm				
Dewatering of sludge at Heerenveen							
	Share sludge	14%	Leeuwarden				
	Electricity	856540	kWh/yr				77
	Polymer 50% acti	190	ton/yr	1700440	MJ/yr		95
	$FeCl_3$ 40%	1985	ton/yr	4492963	MJ/yr		252
	TOTAL CO_2						**425**
Transport of sludge to SNB							**224**
	DM%	4.10%					
	dewatered sludge	20%					
	Dry matter	2271.4	ton DM/yr				
	Sludge cake	11357	ton /yr				
	volume trucks	30	ton/truck				
	total trucks	379	trucks/yr				
	distance	240	km				
	total tonkm	2725680					
	EF CO_2	82	gCO_2/tonkm		(variabelen)		
	EF Nox	*0.44*	*gNOx/tonkm*		*1191*	*kgNOx / yr*	

short cycle CO_2 emission							
	COD influent	441	mg/l				
	COD removal	92%					
	flow	16082265	m^3/yr				
	Total COD conve	7092	ton COD/yr				
	CO_2 emission from COD conversion						
	CO_2 EF from COD (short cycle!!)			1.2	kgCO_2/kg COD remove		**8511**
CO_2 short cycle from digestion	Total biogas proc	1,305,621	m^3/year				
1m3 biogas	65%	Methane					
	35%	CO_2					
	0.6850	kg CO_2/ Nm^3 (20 degrees Celsius)			(Bryns, 2013)		
	Total CO_2 from digestion		313	tones CO_2/year			
CO_2 short cycle from CHP	553	tones CO_2 /year					
CO_2 from pre treatment	Total COD influent		7446	tons COD/year			
	EF STOWA	1.2	kg CO_2/kg COD				
	COD capruring in screening		5%				
	Total CO_2 from pretreatmer		446.76	tons CO_2 /year			

The aim of the workshop

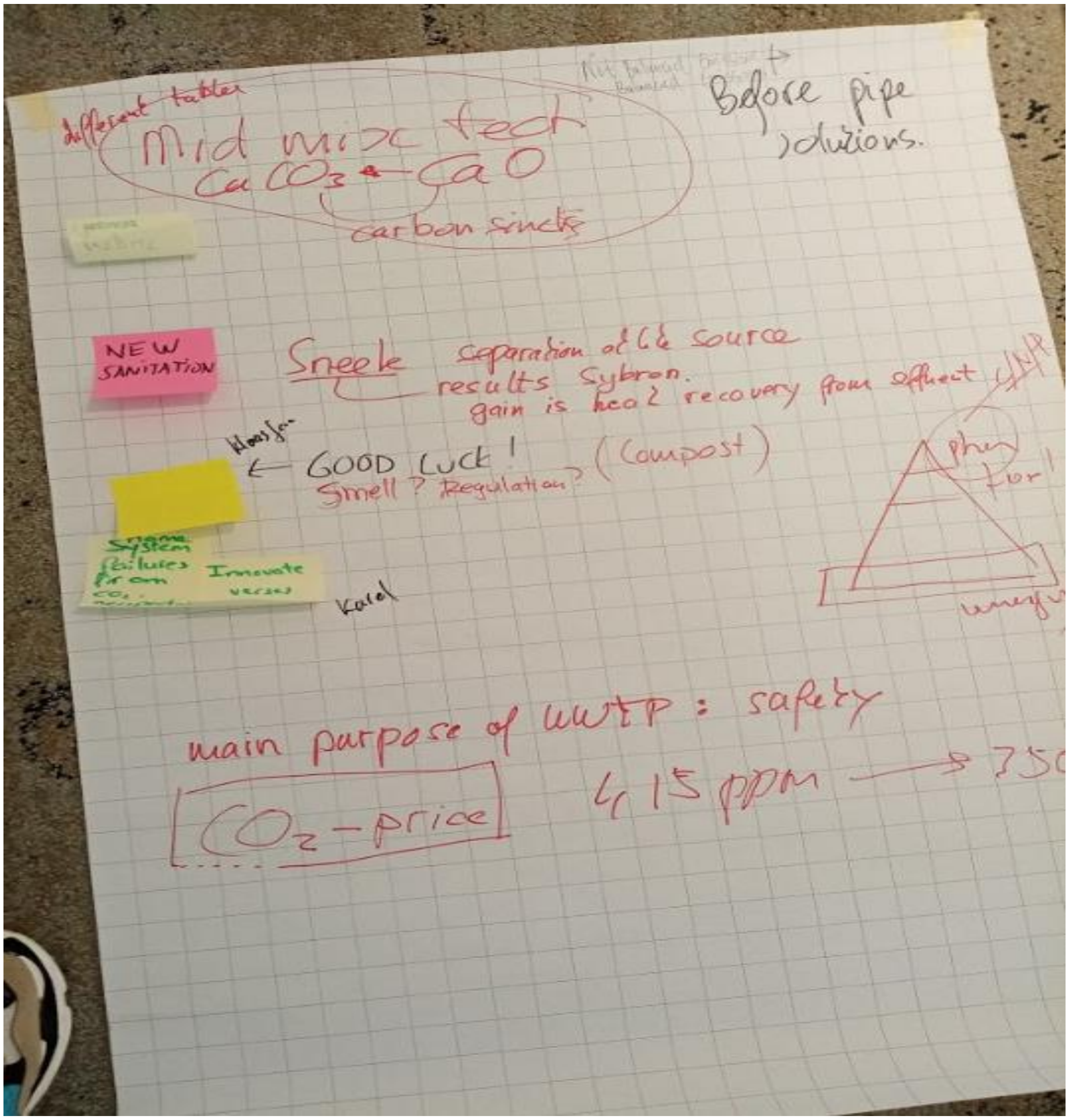
The aim of the workshop is to assist in answering the research questions of this thesis, which are:
Main question:
What is the potential of climate neutrality in the WWTP in Leeuwarden?
Sub-questions:
What are the current GHG emissions of the WWTP?
How much carbon is getting into the process and how much is getting out?
Which technologies and changes are required to capture the carbon in the early stage?

Due to the time limit, the analysis of the utilization of the carbon is excluded from this thesis.
Thus, the focus of the workshop and the thesis is on how to capture the carbon and not on how it will be used.

Open space method:

1st category
Before pipe solutions

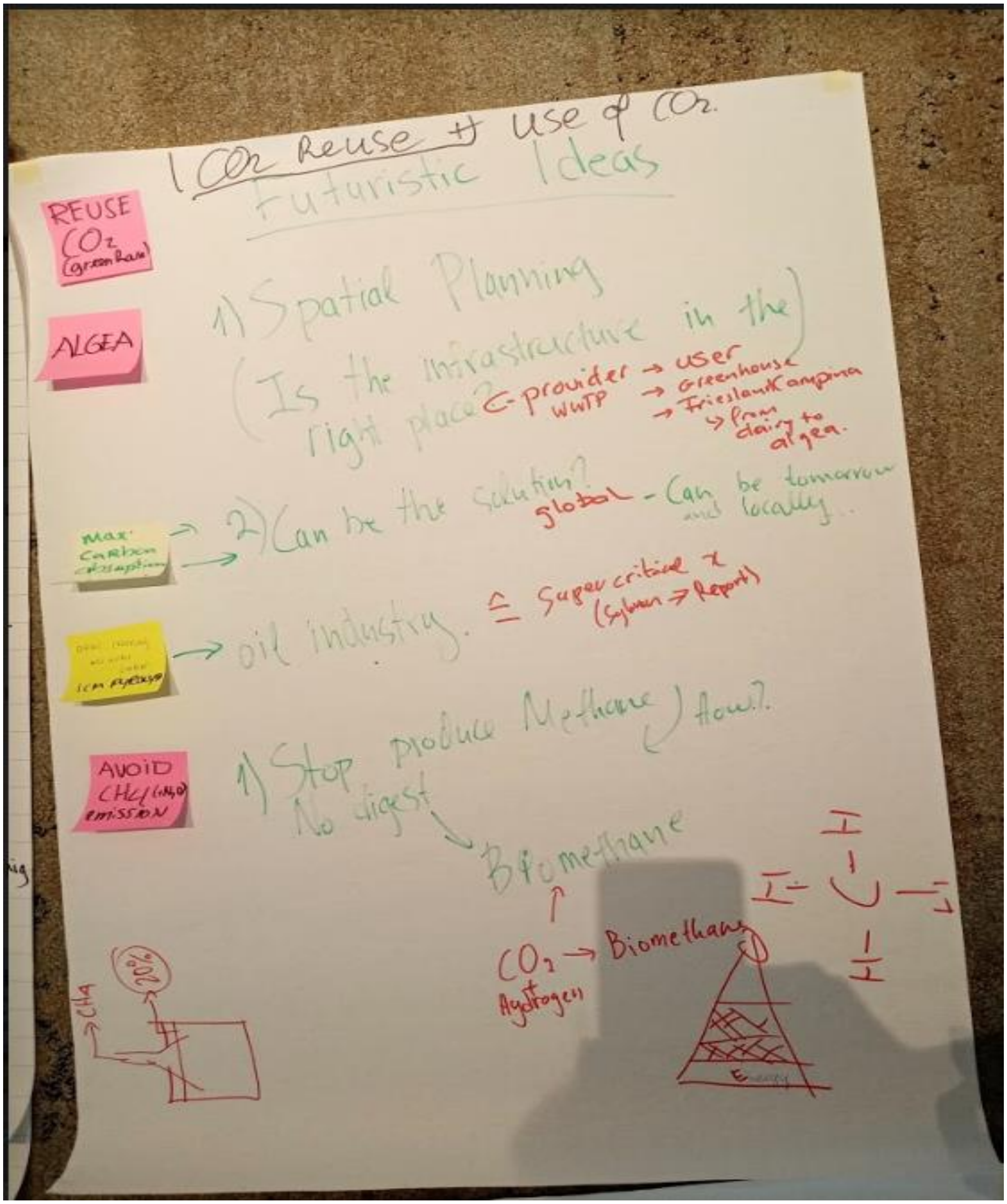
- Reduce carbon input (Is that beneficial? Do we need this carbon in the effluent or is better to reduce?)
- New Sanitation (Separation of water at the source): Example at Sneek -> heat recovery from the effluent
- Direct Reuse (irrigation, compost?)-> What about the smell and regulations? **(Utilization)**



2nd category

Use and reuse of CO_2

- Reuse CO_2 to greenhouses-> Spatial Planning **(utilization)**
  Carbon provider (WWTP) -> Greenhouses, FrieslandCampina (diary and algae)
- Maximize carbon absorption (**Adaptive measure)**
- Direct cracking into usable carbon-> supercritical? (Sybren reports)
- Avoid CH4 and N_2O emissions: Stop production of methane (no digestion)
- CO2 -> Biomethane (**utilization**)

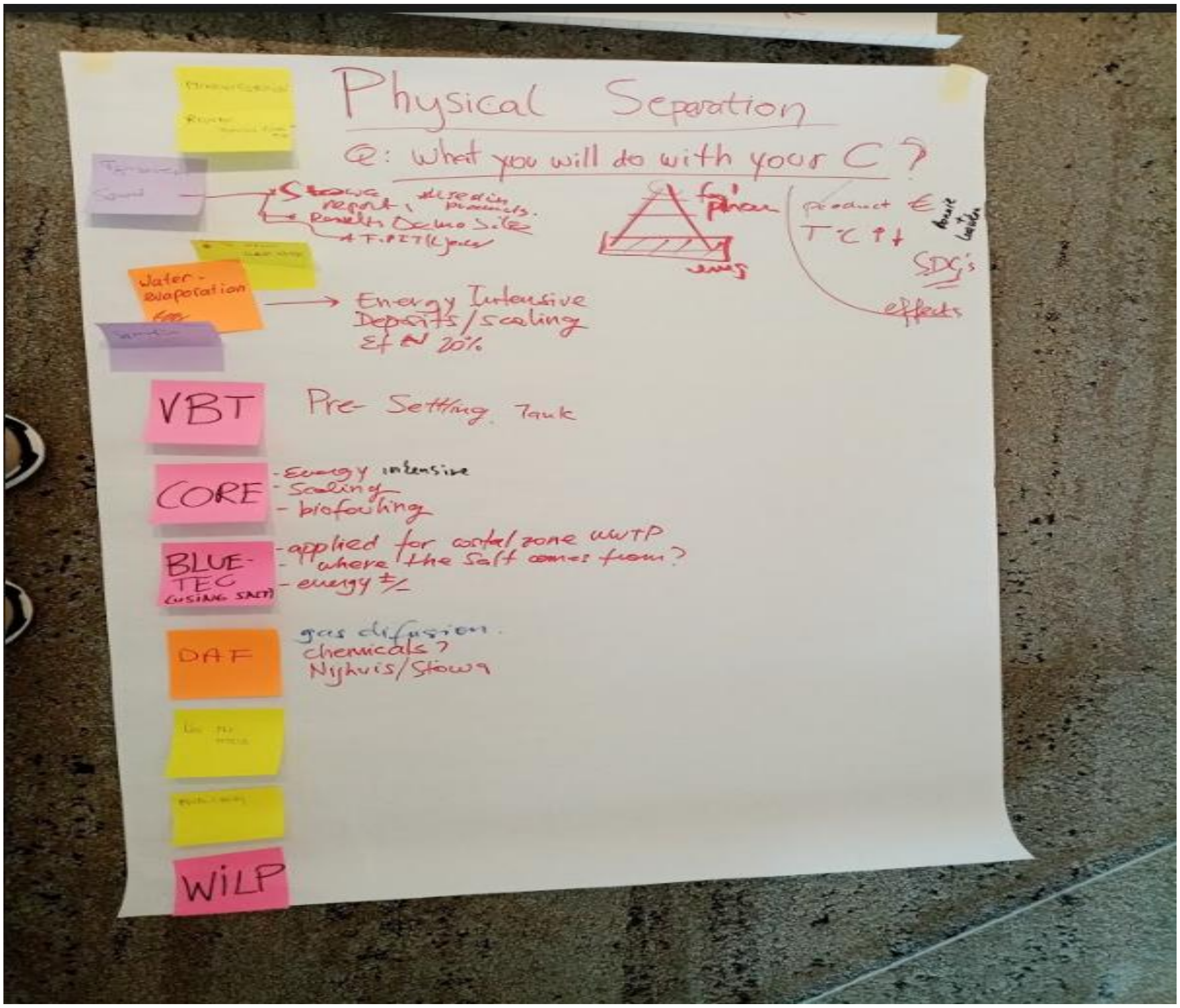


3rd category

Physical separation

- Membranes
- Reverse osmosis
- Vacuum distillation for clean water
- Water evaporation-> Energy-intensive, Deposits, EF N 20%??
- VBT-> Pre settling tank
- Core -> Energy-intensive, scaling, biofuel

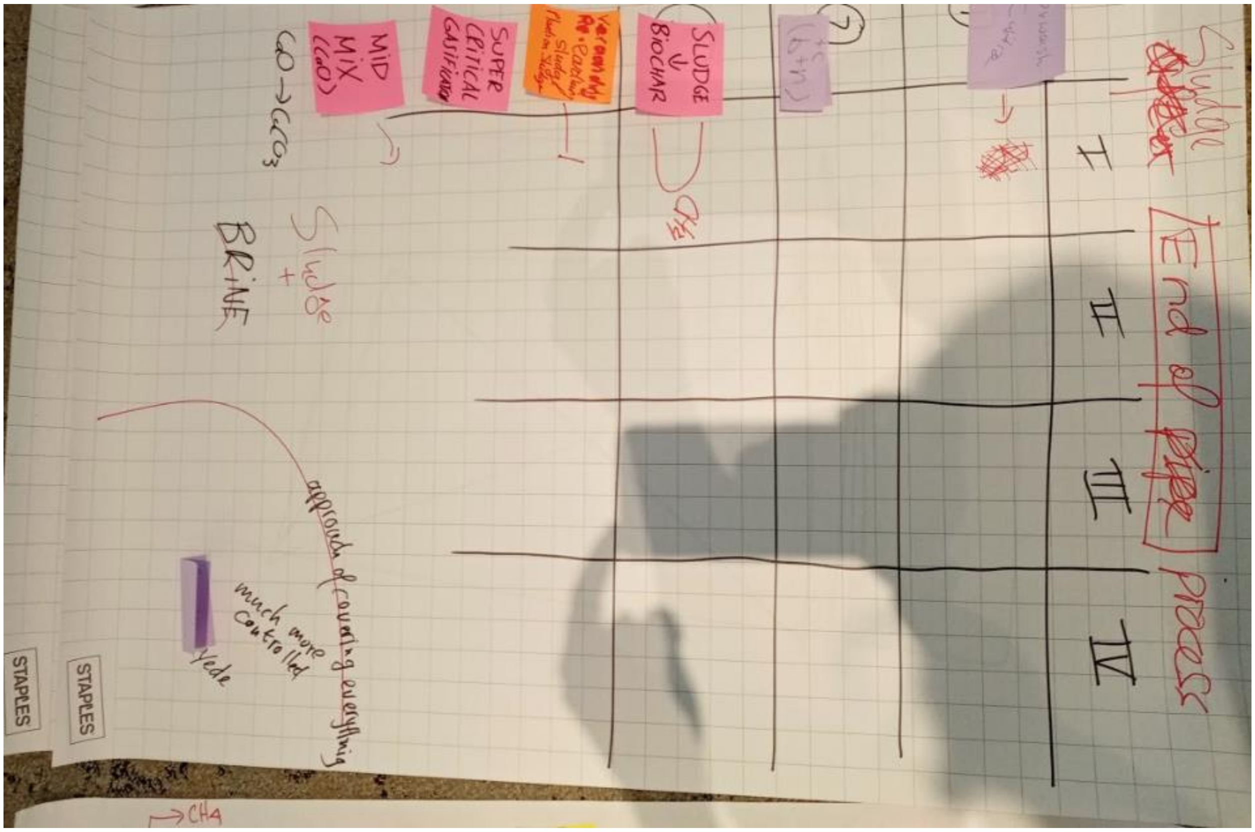
- Bluetech (salt)-> Applied for coastal zone WWTP, where the salt comes from?, energy +/-
- DAF->gas diffusion, chemicals, Nijhuis/ STOWA
- MIcrosieving
- WILP



4th category

End of process

- Torwash?
- Resource   recovery (N,P,C)
- Sludge -□ to -□ Biochar-> CH_4 **(Utilization)**
- Supercritical gasification
- MID MIX (CaO)



It has to be noted that calculations regarding GHG have changed due to recalculation and identification of more emissions associated with the plant.

Participants

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Appendix 2
Carbon redirection

Physical mediated sorption options	**Stage**	**Company**	**Removal Efficiency**	**Characteristics**
Filtration				
DynaSand filter (DSF)	-Pre-Treatment	Axel Johnson Institute	TSS=50-90% COD= less than SS	-Smaller sludge production -No backwashing -Smaller footprint -Lower energy consumption -Chemical saving (reduction of coagulant dosages)
Fuzzy Filter	-Tertiary (can be used for pre-treatment)	Schreiber Corporation	80% (particles of 4micron)	-80% footprint reduction -Pre-filtration for reverse osmosis -High flow rate -High hydraulic loads -Compressible media (unique in the market) -Air scrubbing
Biofiltration (BBF)	-Primary -Secondary -Tertiary -Wet weather flow -Groundwater	BTK	TSS= 61% BOD=43%	-65-60% footprint reduction -Zero chemicals -Low energy consumption
Sals-ness Filter	-Primary (compact system)	Trojan Technologie s	TSS=50% BOD=20%	-No chemicals -The only system that can replace conventional primary treatment -Fully Automated and integrated process -Primary slidge with higher energy value
ClearCove Harvester	-Enhanced Primary Treatment	ClearCove Systems	BOD=65-85%	-100% grit removal -100% gross solid removal -primary sludge with 3x biogas production value -50-65% or energy consumption reduction(conventional) -Enhances membrane solutions
Biofor	-Secondary	SUEZ		-Aerated and non-aerated

Aquazur V	-Tertiary	SUEZ		
Filtrazur	-Tertiary	SUEZ		
Ultra blue	-Tertiary	SUEZ		
Physical mediated sorption	**Stage**	**Market**	**Removal Efficiency**	**Characteristics**
Dissolved Air Flotation				
Captivator	-Primary	Evoqua Water Technologies LLC	SS=99% COD=75-85%	-40% more biogas -Reduction of aeration's energy consumption 20% -Enhances energy neutrality -Reduced footprint
Membrane				
Membrane Bioreactor	-Secondary	Ovivo, Suez, Huber, Alfa Laval	COD= 97% P= 75% N=90%	-Still on the research stage for the pre-treatment application -Energy efficient -Smaller footprint (1/10) -Reliability
Chemical mediated sorption				
DensaDeg Clarifier/Thickener	-Enhanced Primary treatment -Tertiary	Infilco Degremont, SUEZ	TSS=81-88% BOD=54-64% COD=68-78%	-Compact system -uses external sludge recirculation -Lamellar settling with an integrated thickener -No need for thickener -Flexible -Smaller footprint
Actiflo (clarifier)	-Primary	Veolia	TSS= 85% BOD=77-80% COD=75&	-4-8 times smaller footprint than lamella or dissolved air and 50 times smaller than conventional clarifiers -Compact system and ultra-rapid -Use of iron or aluminium salt
CoMag	-Enhanced Primary -Tertiary	Evoqua, Envirex	TSS<5 mg/l T-P<0.2 mg/l T-N<3 mg/l	-Use of magnetite -Recovery of nutrients -Embryonic stage -Possible without tertiary treatment

				-Smaller footprint
Sedipac 3D	-Primary	SUEZ		
RapidSand(ballasted flocculation)	-Primary	WesTech	??	-90% smaller footprint derived from sedimentation - Coagulation, flocculation,clarification,separation -Quick start-up
Pulsagreen	-Tertiary	SUEZ		
Biological mediated sorption				
Adsorption/bio-oxidation High rated activated sludge	-Secondary		TSS=80-95% COD=70-80%	-Unaffected nutrients -High efficiency of removing -A-stage,B-stage
Contact stabilization/ Low rated activated sludge	-Advanced Primary		COD=86% BOD=87& TSS=82%	-Short hydraulic retention time in the contact reactor -High rate contact stabilization (future)
Meteor MBBR and IFAS	-Moving bed biofilm reactor			
Greenbass	-Secondary			

Based on STOWA, SUEZ, Sancho & Cortina, https://www.sciencedirect.com/science/article/pii/S0048969718329759

Carbon redirection

Physical mediated sorption

Filtration

DynaSand Filter: The dynamic sand filtration of urban wastewater in a pre-treatment solution with high efficiency of removing suspended solids. The main principle of the system is that the sand bed operated at the same time as a flocculation reactor and filter, with no extra need for flocculation, sedimentation or flotation step.

Fuzzy Filter: It is compressible media filter that is made from a high-grade polymer. The greater the compression on the media the smaller the porosity of the media bed and the better the particles removed. It is highly;y flexible and reliable.

BBF: It is a high-rate upflow filtration system that can replace primary clarifiers. It combines biological treatment and physical filtration in a single reactor. It is already expanded to wet weather flow treatment technology.

In the **Salness Filter System** the solid separation, sludge thickening and dewatering are performed in one compact unit. It provides primary treatment with considerable lower sludge handling, transportation and disposal costs.

ClearCove Systems: With ClearCove Systems the capturing of the organics takes place upfront and thus, it is able to supply an energy-rich fuel source for biogas production (3 times higher energy content), it can increase the plant's capacity by reducing the time and the volume required for secondary treatment.

Biofor: The BioFOR process is used primarily for the removal of BOD, TSS and ammonia pollution in secondary and tertiary treatment. Biofiltration was developed by SUEZ in the 1980s as part of the Biofor® process, which is an upflow biological reactor. The Biolite, which is the filtering material, is placed in the reactor and serves as a support for microorganisms. Feedback has allowed a selection of varied and optimal sort of Biolite and aeration system and has led to developing two main families of Biofor®: "aerated" and "non-aerated" Biofor®. The effluent to be treated is continuously fed into a biological reactor called a "biofilter", passing through filtering materials that retain the suspended solids. Carbon and/or nitrogen pollution is eliminated thanks to the development of natural bacteria into a fixed biofilm (purifying biomass) on mineral support that is also natural. A filtering material washing is regularly activated to restore the filtering and purifying capacity of the biofilter.

Dissolved Air Filtration

Captivator: This system combines the liquid separator and sludge thickener. It is very efficient in the removal of particles and can reduce the particle load to the filters compared to direct filters. In the Captivator System, primary clarification and separate sludge thickening is replaced with a modified contact stabilization process in front of DAF, which is an aerated tank that is fed both raw influent and waste activated sludge.

Membranes

Membrane Bioreactor: Aerobic MBRs can be configured similarly to these modified CAS processes, in essence, the biological function remains unaltered by the membrane: the membrane simply replaces the secondary clarifier.
Municipal MBRs are often implemented as a retrofit to an existing CAS process. Adapting the CAS to an MBR permits an increased flow through the process as well as an improved treated water quality, which is often of practical significance when consents/permits for discharged nutrients in the wastewater are tightened by the regulators.

Chemical mediated sorption

DensaDeg system(lamellar settling sludge thickening): It combines a physical-chemical settling tank (optimised flocculation) by using external sludge recirculation. It combines the principle of lamellar settling with an integrated thickener. It is very rapid and automated commissioning which means various different applications using the same equipment.

Actiflo: ACTIFLO® is a high rate compact water clarification process in which water is flocculated with micro sand and polymer in a Turbomix® draft tube. The microsand enhances the formation of robust flocs and acts as ballast, significantly increasing their settling velocity. The unique characteristics of the resulting microsand ballasted flocs allow for clarifier designs with very short retention times, high rise rates and extremely compact system footprints that are up to 50 times smaller than other clarification processes of similar capacity.

CoMag: The CoMag® system uses magnetite – fully inert iron ore particles – to enhance the clarification process. The system settles chemical floc up to 30 times faster than conventional treatments, enabling plants to increase capacity and enhance clarifier performance.
Additionally, the CoMag system can reduce plant investment costs by limiting clarification tank size. It can achieve total phosphorus down to 0.05 mg/L and can achieve UV

transmittance greater than 75% when integrated into any type of coagulation/flocculation process or clarifier. The CoMag system also features an internal recycle from clarifier underflow to process tanks, which reduces chemical consumption. Magnetite ballast, which is added into the chemical reactor to accelerate settling, is continuously separated from the clarifier underflow stream. Typically, 99 percent of the magnetite is recovered and reused in the system.

RapidSand: The WesTech RapiSand™ ballasted flocculation system is a high-rate clarification process using rapid mixing and multi-stage flocculation, followed by sedimentation. RapiSand sedimentation is extremely fast and can be applied in a wide variety of suspended solids removal applications. The typical uses of RapiSand include expanding plant capacity, minimizing plant footprint, providing fast start-up capabilities, and providing great performance characteristics.

Biologically mediated sorption

High rated activated sludge: The high-rate activated sludge (HRAS) systems are shifting the energy-intensive processes to low-energy and sustainable technologies for wastewater treatment. In order to recover energy-rich organic carbon from wastewater, the HRAS system can be an optional technology for moving towards energy neutral (or positive) treatment processes.

Contact stabilization: The contact stabilization process has been applied in full-scale plants which treat domestic wastewater. The main advantage of this process is the short hydraulic retention time (HRT) in the contact reactor (CR), allowing treatment volumes significantly lower than in

Appendix 3

5.3 Anaerobic digestion /Power to biomethane

In chapter 4 in the Core process anaerobic digestion is included. Further it was also mentioned that Bio Electrochemically assisted microbial reactor (BEAMR), can generate H2 (paragraph 4.3). Based on these facts, the four-year project of "Power to biomethane, bio-P2G" (P2G) which is managed by Hanze University of Applied Sciences Groningen, found interesting. The P2G project is based on the broader need for energy transition with the elimination of GHG emissions. Its separated implementation in the WWTP is possible and according to Bekkering et al, and currently is in laboratory scale. As mentioned in paragraph 3.6 during anaerobic digestion of organic matter, a mixture of gases is generated. In this mixture, 35% of CO_2 is included and solutions have to be reached in regards with its capturing instead of being emitted in the atmosphere. This CO_2 is responsible for 10% of the total GHG emissions calculated. During thermal decomposition, a mixture known as syngas consisting of CH4, CO_2, carbon monoxide (Henceforth: CO) and H2 has resulted. Therefore, according to Bekkering et al. (2019), the biological conversion of H2 and CO_2 into CH4, with the assistance of bacteria such as hydrogenotrophic methanogenic archaea, can occur. These methanogens, called hydrogenotrophic, are catalysed by enzymes at temperatures between 35-70 degrees Celsius at atmospheric or elevated pressure.

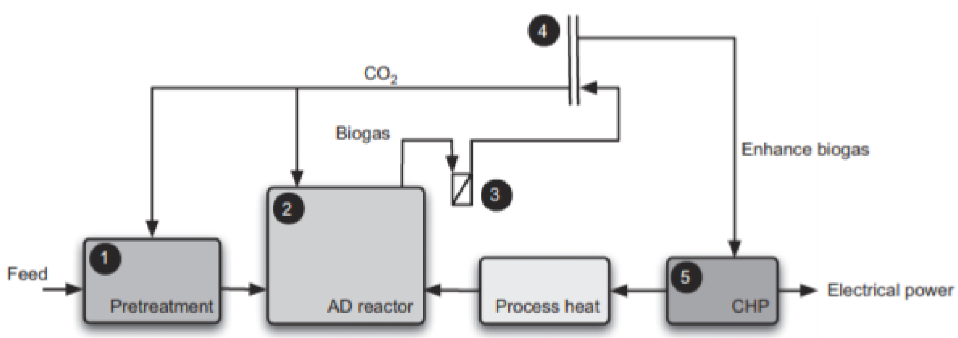
According to Bekkering et al., Sabatier reaction or gas phase methanation is the chemical conversion of H2 and CO2 into CH4. It was estimated that 30% of the energy in H2 gas turns into heat and the reaction demands high temperatures and a catalyst for which, nickel is mostly used. Based on Bryns et al. (2019), with the chemical storage, power can be converted directly into hydrogen gas (Henceforth: H2) via electrolysis of water. Thus, electrolysis is the conversion of electrical energy to chemical energy in the form of hydrogen, with oxygen as a potential by-product of the process (Bekkering et al., 2019).

Currently, there are three technologies with respect to the electrolysis process. Alkaline electrolysis (AWE), proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC). Essential to mention at this point that the electrolysis process requires high energy, which means that can be considered as a sustainable option only in combination with renewable energy production on-site. Further, difficulties have been identified with the explosive and flammable characteristics that it has, resulting in concerns with safety. According to Bekkering et al. (2019), CH4, and therefore biological conversion, is more accessible to handle than hydrogen gas, since, in The Netherlands, there is excellent maintenance of infrastructure, transportation and storage of CH4 and H2 storage and maintenance are still under research.

Therefore, it can be said that the biological process has an advantageous position over the chemical processes. The lower temperature and pressure associated with the biological methanogenesis, the absence of sensitive catalyst such nickel for chemical reaction, make chemical conversion less preferable. Biological processes enhance the operation since are adaptive and flexible systems (Can I put Sybren as a reference?). Further, the biological conversion of CO_2 to methane results in almost 100% which means that can be used under the Dutch standards for green energy, and therefore as transportation fuel even for WF. Based on these, this analysis continues with the biological conversion of CO_2 and H2 to CH4.

Biological conversion of carbon

Autotrophic methanogenic bacteria utilise H2 during the anaerobic conversion of CO_2 into CH4 (Zhang et al., 2008; Alvarado et al., 2005). Usually, in these environments, H2 is rapidly utilised even when is in low concentrations. Alimahmoodi and Mulligan (2008), based on a laboratory scale with an up-flow anaerobic sludge blanket (Henceforth: UASB) reactor, supported that the rate of methane production can be doubled with the introduction of CO_2 at a fixed loading rate. Figure below presents the in-situ biological conversion of CO_2 to CH4, were in stage 1, pretreatment stage enhances hydrogen and volatile fatty acids streams to create. In stage 2 the existing anaerobic digesters are shown without any change associated. Element 3 in the figure is the water trap which removes water from the biogas stream and number 4 is the membrane filter which separates CO2 from the anaerobic digester stream. Finally stage 5, the enhanced biogas stream can be utilized by the existing CHP engines. As shown, the heat generated from CHP facilities is returned into the anaerobic digesters.



Table, In-situ Bioconversion in 5 stages for the WWTP.

Appendix 4

Energy neutrality goals

The main ambitions of the Climate Agreement are[9] formulated as follows:

- 30% more energy efficient working between 2005 and 2020
- 40% self-sufficient through own renewable energy production in 2020
- 30% reduction in greenhouse gas emissions between 1990 and 2020
- 100% sustainable procurement from 2015

In the Energy Agreement for Sustainable Growth,[10] more than 40 organisations agreed on climate and energy. The agreement is aimed at the following objectives:

- savings in final energy consumption of 1.5% per year on average
- 100 petajoules of energy savings in the final energy consumption of the Netherlands by 2020
- an increase in the share of renewable energy to 14% by 2020
- a further increase of this share to 16% in 2023
- at least 15 000 full-time jobs, to be created for a significant part in the first years

Green Deals

Wetterskip Fryslân itself and through the Union of Water Boards has concluded several Green Deals. These are deals in which the central government has made agreements with other parties to give space to sustainable initiatives from society. The table below shows the Green Deals relating to energy.

Table 7: Green Deals

Characteristic	Partner	Description	Theme	Start
GD057	UvW	Energy plants and nutrient recovery	Energy and raw materials	2011
GD082	WF	Applying new water technologies from the Northern Netherlands	Energy, raw materials and innovation	2012
GD195	UvW	Energy Union of Water Boards - Empire	Energy	2016
GD206	UvW	Pilots Regional Energy Strategies	Energy	2016

CH4 reduction

As presented in paragraph the contribution of CH4 to the total carbon footprint was estimated 12% (1882 tons CO_2 eq/year). According to Campos et al. (2016), but also after discussion with experts of WF, it was found that essential minimization of CH4 can occur if the thickeners and sludge buffers are totally covered in order to evade gas leaks and their associated emissions are captured by hoods. Further, those can be burnt in the torch or be stored and utilized.

N2O reduction

According to WF experts, the current nitrification and denitrification processes but also the plant's conditions of operation provide the low contribution of 133 tones N_2O annually. However, even lower contribution can be reached by low dissolved oxygen concentration on nitrification and the presence of oxygen in denitrification process, low COD/N ratio in the denitrification process, sudden changes of pH and dissolved oxygen, ammonia and nitrite concentrations and high nitrite amounts in nitrification and denitrification process (Campos et al., 2016; Law et al, 2012; Kampschreur et al, 2009). These mean that N2O can be minimized under high solid retention times (Henceforth: SRT) in order to conserve the level of ammonia and nitrite concentrations low (Law et al., 2011)

Indirect GHG emissions

Electricity used

Based on WF Energy Agenda and Climate Agreement, the installation of 40000 solar panels have already started. The renewable energy for the WWTP in Leeuwarden will replace 40% of the current electricity purchasing. Additionally, it was mentioned that WF has guarantee of origin for green electricity, which means that these emissions associated with the electricity purchasing, administratively does not count in the WF carbon footprint. Therefore, 15% associated with the energy purchased will not considered in the future measurements.