DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

Carbon Footprints for wastewater treatment plants

Master thesis within environmental science

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Abstract

Human activities have a significant impact on rising greenhouse gases (GHGs) in the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC) AR5 III, wastewater treatment plants (WWTPs) potentially emit a large amount of nitrous oxide (N_2O) and methane (CH_4) with relatively high global warming potential (GWP). N_2O is emitted primarily in the nitrification and denitrification steps of the wastewater treatment processes. CH_4 is generated to a large extent via the anaerobic wastewater treatment process. One efficient tool to assess the environmental impact of direct and indirect GHGs is a carbon footprint calculation tool (CFCT). In this master thesis, the carbon footprint calculation was based on operational data, literature emission factors (EFs), and on-site measurement of GHGs at the largest municipality WWTP in the Nordic countries Rya WWTP. The carbon footprint (CF) analysis suggests that the major positive contributors for rising CF were firstly direct emissions of N_2O from the wastewater treatment process and secondly, indirect GHG emissions through chemicals use. Direct emission of CH_4 in the sludge pile was the third major contributors to the total CF. Broad range of EF for N_2O emissions were recognized in the literature. The energy bought and utilized was produced by renewable sources, wind, and solar power, which has low indirect GHGs emissions. Proper extension of the length of the anoxic phase in denitrification could be a potential mitigation method to regulate N_2O emission. Reduce the duration of sludge storage, a larger ratio of the sludge used on farmland, shift to environmental labeled district heating, utilize bio-based chemicals withe less climate impact, and further efforts to increase bio-gas production are fundamental activities for reducing the carbon footprint of Rya WWTP.

Key words: Carbon Footprint (CF), Greenhouse gas (GHG), Nitrous oxide (N_2O), Methane (CH_4), Wastewater treatment plant (WWTP), Global warming potential (GWP), Intergovernmental Panel on Climate Change (IPCC), Emission Factors (EFs).

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List of Abbreviations and Markings

AR4: Fourth Assessment Report
AR5: Fifth Assessment Report
BNR: Biological Nutrient Removal
BOD: Biochemical Oxygen Demand
CC fb: Climate-Carbon feedback
CF: Carbon Footprint
CFCT: Carbon Footprint Calculation Tool
CH_4: Methane
CO_2: Carbon Dioxide
CO_2e: Carbon Dioxide Equivalent
COD: Chemical Oxygen Demand
DO: Dissolved Oxygen
EFs: Emission Factors
FU: Functional Unit
GHG: Greenhouse Gas
GWP: Global Warming Potential
H_2O: Water vapor
ICIA: Life Cycle Impact Assessment
IPCC: Intergovernmental Panel on Climate Change
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
N: Nitrogen
N_2: Nitrogen gas
N_2O: Nitrous Oxide
NH4: Ammonium
NIR: National Inventory Report
NO_2: Nitrite
NO_3^-: Nitrate
O_3: Ozone
P: Phosphorous
PE: Personal Equivalent
SAR: Second Assessment Report
UNFCCC: United Nation Framework Convention on Climate Change
US EPA: United States Environmental Protection Agency
WWT: Wastewater Treatment
WWTP: Wastewater Treatment Plant

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1 Introduction

1.1 Background

Anthropogenic greenhouse gases (GHGs) emissions in recent decades have shown a strong association with the effect of global temperature rise and pose hazards for natural and human systems (IPCC, 2014). There are consequences of climate change such as changes in precipitation, rising mean surface temperature, and sea-level rise and extreme weather (IPCC, 2013). Intergovernmental Panel on Climate Change (IPCC) has continually indicated the effect of the rising mean surface temperature and published future scenarios of climate change.

The primary GHGs in the earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) (IPCC, Glossary). Aside from CO_2, other GHGs such as N_2O and CH_4 are also emitted in larger quantities now than in pre-industrial times (NIR Sweden, 2019). According to the defined targets for controlling emissions in the United National Framework Convention on Climate change (UNFCCC), Sweden has an ambitious, long-term target and stable climate policy. Sweden should have no net emission of GHGs into the atmosphere and then achieve negative emissions by 2045. Therefore, the man-made emissions in Sweden are to be at least 85% lower by 2045 compared with 1990 (NIR Sweden, 2019).

In IPCC guidelines the wastewater treatment (WWT) is highlighted in national GHG inventories because of the emission of N_2O and CH_4 (IPCC, 2006 and IPCC, 2019). According to the United States Environmental Protection Agency (US EPA), the N_2O emissions from wastewater treatment have increased by 44% from 1990 to 2014 in the United States (US EPA, 2016). Consequently, the evaluation of the environmental impact of wastewater treatment plants (WWTPs) is gaining increasing attention regionally and globally (Guo *et al.*, 2018).

Traditionally, WWTP operation aims to remove pollutants from wastewater to keep water quality in high standards for public health and environmental protection. Currently, novel ideas are developed to move towards sustainability in WWTPs. Sustainability is a broad concept in which economic, environmental, and social aspects of WWTPs are targeting (Sweetapple *et al.*, 2015). Each of those aspects can have sub-divisions in to the large extent of factors. Reducing GHG emissions from WWTPs could be one of the key factors of sustainability.

To mitigate GHG emissions from WWTPs, many measures are carried out globally. Life Cycle Assessment (LCA) can quantify the environmental impacts of a process and includes more impact categories such as toxicity, water use, and eutrophication. However, carbon footprint (CF) only focuses on the climate impact category GHG emissions. The overall impact of WWTPs on climate change could be determined by CF as a novel measure of sustainability in the wastewater sector (Gustavsson and Tumlin 2013; Yoshida *et al*., 2014; Delre *et al.*, 2019).

1.2 Project description and objectives

The purpose of this project is to develop and update the user-friendly tool for CF calculations of a WWTP, developed at Rya WWTP in Gothenburg, one of the largest municipalities WWTP in the Nordic countries. The tool is based on Microsoft excel and named Carbon Footprint Calculation Tool (CFCT) for WWTPs (CFCT, 2014). The calculation tool was developed during a project on carbon footprints of Scandinavian WWTPs by Gustavsson and Tumlin (2013) for the Swedish Water and Wastewater Association.

The project aim is to help WWTPs to become more active in decreasing their CF, based on calculations with this efficient excel tool.

In this master thesis, initially, the climate impact from Rya wastewater treatment processes have calculated and then realized that which processes had substantial contributions. Furthermore, the reasons for differences in CF sectors of Rya WWTP along with the impacts of using different emission factors (EFs) have studied. Then, some improvement strategies have suggested. Accordingly, the research questions of this study were highlighted bellow:

1) How large is the climate impact from Rya WWTP?
2) Which processes have substantial contributions to the climate impact and how should they be mitigated?

More information about project descriptions and implementations are presented in section 3.2.1 (CFCT).

Table 1. Defined tasks in the project of CF for WWTPs

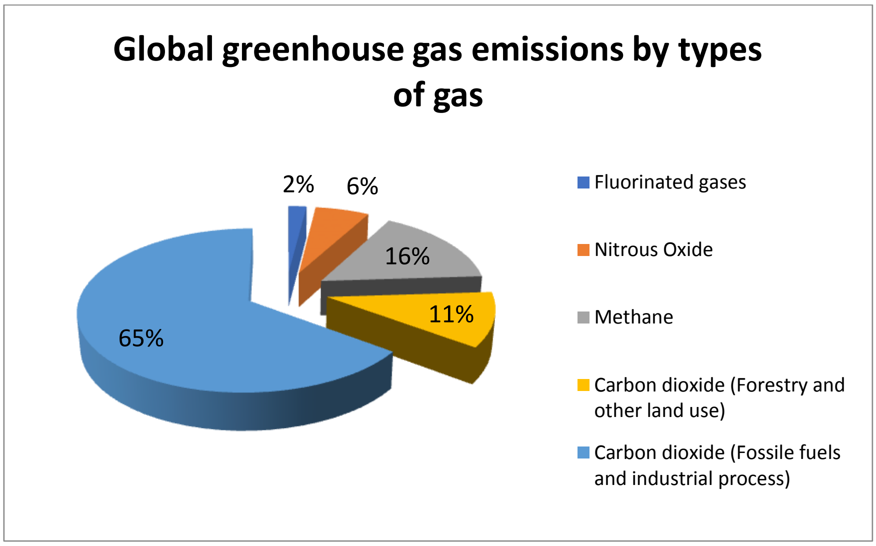
Items	**Tasks**
1	English translating and updating CFCT – Collecting data from internal operational reports.
2	Analyze and compare CF of years 2018 and 2019.
3	Send out a survey about climate impact to 10 chemical suppliers.
4	Updating some values (EFs, Chemical's production climate impact and GWPs).

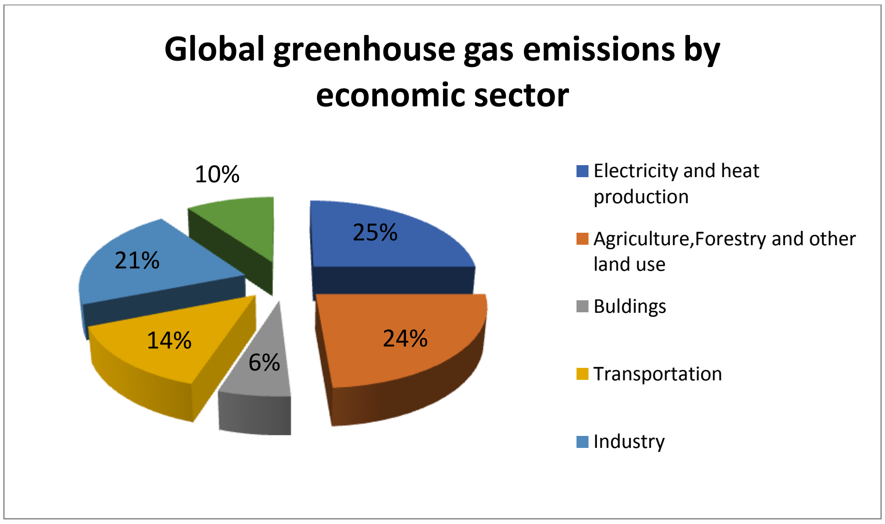
2 Literature review

2.1 Greenhouse gases (GHGs)

2.1.1 Emission sources

Three major GHGs are CO_2, CH_4, and N_2O. Total GHG emissions have illustrated below according to the types of GHGs and the economic sector respectively in Figures 1a and b (IPCC, 2014). The wastewater sector generates up to 3% carbon emissions globally (Xu, 2013), and 0.37% of total national carbon emissions are produced in the USA (Wang *et al.*, 2016).





Figures 1a and b. IPCC 2014, based on global emissions from 2010. Details about the sources included in these estimates can be found in the Contribution of Working Group III to the AR5 of the IPCC.

2.1.2 National Inventory Report 2019, Sweden

Sweden's national inventory report (NIR) organizes the yearly based submission for the second commitment period from 2013 to 2020 which was established under the Kyoto Protocol. According to the commitment, parties were committed to decreasing GHG emissions at least 18% below 1990 levels. Summary of national emissions and removal trends 2019 in Sweden suggest that total GHG emissions have decreased by around 0.5 % and 26% compared to 2016 and 1990, respectively.

That report proposes the national emissions of CO_2 were about 27% lower in 2017 compared to 1990. The largest source of CO_2 is accounted for in the energy sector for transport which is about 85% of the overall CO_2 emissions in Sweden.

CH_4 emissions have been reduced by 39% since 1990, majorly related to the measures in the waste sector. Also, emissions have been reduced in the agriculture sector. In one year from 2016 to 2017 emissions have decreased by 0.8%. CH_4 corresponds to 9% (4.5 million tons CO_2 equivalent) of the total GHG emissions by 2017 and majorly rises from agriculture, landfills, and fossil fuels burning in the energy sector.

N_2O emission corresponds to the 4.9 million tons of CO_2 equivalent (CO_2e) in 2017 (9% of total GHG emissions), which is a decrease of about 15% compared to 1990 and increased by 6.6% compared to 2016. The major source to generate N_2O implies it is made deliberately by the agriculture sector (about 78%).

2.1.3 Global warming potential (GWP)

Global warming potential (GWP) is defined as the cumulative radiative forcing including direct and indirect effects, integrated over some time from the emission of a unit mass of gas relative to some reference gas. IPCC has selected CO_2 as a reference gas and its GWP is equal to one (1). GWP values allow you to compare the impacts of emissions and reductions of different gases. The gases with relatively long atmospheric lifetimes and with global average concentrations are CO_2, CH_4, N_2O, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride (SF_6), and Nitrogen trifluoride (NF_3) (IPCC, 2007; IPCC, 2014).

There are different GWPs mentioned for CH_4 and N_2O in literature and IPCC reports. According to the Anthropogenic and Natural Radiative Forcing report in IPCC 2013, the value 34 for CH_4 and 298 for N_2O was specified with climate-carbon feedback (CC fb). In this master thesis, also the GWP with CC fb was used and analyzed (Table 2).

Table 2. Global warming potential (GWP) in 100-year time horizon, IPCC 2014 AR5, fourth assessment report 2007 (AR4) and second assessment report 1995 (SAR), IPCC 2013 with climate carbon feedback (CC fb)

Common Name	Chemical Formula	GWP for 100-year time horizon			
		SAR	AR4	AR5	AR5 with CC fb
Carbon Dioxide	CO_2	1	1	1	1
Methane	CH_4	21	25	28	34
Nitrous Oxide	N_2O	310	298	265	298

2.1.4 Carbon Footprint (CF)

Despite many different definitions of CF (Wiedmann and Minx, 2008), this concept in this literature review is referred, to sum up, the amount of direct and indirect GHG emissions which are caused by a WWTP within the defined system boundary. The different sorts of GHGs are transformed into CO_2e by various ranges of GWPs at defined time horizons *(*Gustavsson and Tumlin, 2013*).*

2.1.5 Direct and indirect GHGs emissions

The three most important GHGs are emitting from a WWT process from least to most dominant named CO_2, CH_4, and N_2O (Chen, 2019). GHG emissions from WWTPs classify to direct and indirect forms that can be estimated in a CF assessment (IPCC, 2014).

Direct emissions from WWTPs are including non-biogenic CO_2, CH_4, and N_2O which emit within system boundaries. These emissions originate from treatment processes like the biological treatment phase and vehicles such as cars and trucks. The CO_2 emission from secondary biological treatment is not included in the direct emissions as it is a biogenic source which means the produced CO_2 is equivalent to the CO_2 that was extracted from the air through photosynthesis (IPCC, 2006).

Indirect emissions are an effect of activities within system boundaries but occur outside defined boundaries. These emissions come from effluent, external energy production, chemical production, transports, composting of sludge, and landfills. Study shows that indirect emissions have a large contribution (about 60%) of GHG emissions in WWTPs *(*Kinnear *et. al*, 2010). The final product of the sludge treatment, bio-solids, needs to be carefully considered in terms of indirect GHG emissions. Fossil fuel combustion that comes from the transportation of bio-solids is an important source of emissions. Moreover, after the disposal of effluent into water bodies like lakes or seas, N_2O can be formed, thus contributing to the indirect emissions (IPCC, 2006).

2.1.6 Nitrous oxide (N_2O) and Methane (CH_4) emission

According to the IPCC report, CH_4 is 34 times and N_2O 298 times stronger GHGs than CO_2 in the atmosphere in 100 years' time horizons (IPCC, 2013). CH_4 and N_2O stay in the air for about 10 and 114 years, respectively (Solomon *et al*. 2010).

Degradation of nitrogen (N) compounds in the wastewater like urea, nitrate (NO_3^-), and protein, e.g are major contributors to generate nitrous oxide. Direct emissions of N_2O may be produced in both nitrification and denitrification in centralized wastewater treatment systems. Both processes can happen in the plant as well as in the water bodies receiving effluent. Nitrification is an aerobic process that converts ammonia and other N compounds into NO_3^-, whereas denitrification occurs under lack of free oxygen, and involves the biological conversion of NO_3^-into dinitrogen gas (N_2). ''N_2O can be an intermediate product of both processes but is more often associated with denitrification'' (IPCC, 2006). Some operating parameters, like dissolved oxygen (DO), pH, ammonium (NH_4^+) and nitrite (NO_2) concentration, and environmental conditions (e.g. temperature), have an impact on the N_2O production in the WWTPs. Moreover, lack of organic substrate which means low chemical oxygen demand (COD) to N (COD: N) could be responsible for N_2O emissions. (Desloover *et al*., 2012; Kampschreur *et al*., 2009; Massara *et al.,* 2017; Chen, 2019).

Anaerobic wastewater and sludge treatment processes will produce a large amount of CH_4 when organic matter is removed from water due to CH_4 low solubility and high mass transfer capacity (Chen, 2019). The amount of CH_4 production depends on the biodegradable substance, temperature, and sort of treatment processes (IPCC, 2006). In high temperatures, the rate of CH_4 production will increase. Below 15 degrees centigrade the methanogens are not active so then considerably less CH_4 is formed (IPCC, 2006).

Similar to the WWT process, GHGs are emitted during the composting process. CH_4 is formed in the anaerobic sections of the composting piles (Brown *et al*. 2008) and N_2O in different steps of the degradation of the N compounds (Sánchez-García *et al*. 2014).

The amount of degradable organic material is a major factor in determining the CH_4 generation potential of the wastewater. Two common parameters that measure the organic material of the wastewater are biochemical oxygen demand (BOD) and COD. Wastewater with higher COD or BOD concentrations will generally generate more CH_4 than wastewater with lower COD or BOD concentrations (IPCC, 2006).

Discharging effluent with a high level of N to the water bodies like lakes, rivers and, seas will have another environmental impact i.e. eutrophication, which would result in algae bloom and oxygen depletion in the water. The trade-off between the GWP of N_2O and the eutrophication potential of N is clear. If we optimize for low N_2O emission from the WWT processes (direct emission from the treatment) the abatement ratio of N from the wastewater might go down, and slightly more N will reach the recipient, causing eutrophication. Then, there will be a trade-off, either higher N_2O emissions or good abatement ratios for N, or low N_2O emissions and slightly worse abatement ratio for N.

2.2 Wastewater treatment plant (WWTP)

Wastewater treatment is an essential societal service that protects the environment and human health by reducing the sewage nutrient load in the ecosystem. Generally, domestic wastewater is treated in a centralized plant. Centralized wastewater treatment methods can be categorized as primary (Mechanical), secondary (Biological), and tertiary (Chemical) treatments (Allaby and Park, 2013*)*. Physical screens remove larger solids like papers or cloths from the wastewater in the primary treatment phase. Remaining particulates are passing to the next phases. In secondary treatment, a combination of biological processes that promote biodegradation by micro-organisms will happen (IPCC, 2006). In this phase, microorganisms initiate to nitrifying and denitrifying to reduce the N as well as mineralize and reduce dissolved organic carbon (Bitton, 2005). These may include aerobic stabilization ponds, trickling filters, and activated sludge processes, as well as anaerobic reactors and lagoons. For further purifications of wastewater, the tertiary treatment is used to remove contaminants, pathogens and, nutrients residual such as N and phosphorous (P).

2.2.1 Wastewater treatment plants in Sweden

Wastewater treatment in Sweden is happening both in municipal WWTPs and in some industries. CH_4 and N_2O are emitting from these activities.

About 500 municipal WWTPs are operating in Sweden with treatment capacity for more than 2,000 personal equivalents (PE). About 95 % of the wastewater is treated mechanically, chemically, and biologically. A wide range of both municipal and industrial WWTPs are using aerobic processes were no CH_4 generated due to using aeration in the WWT process. According to the NIR 2019, there were only six plants were using anaerobic wastewater treatment in Sweden in 2017.

In some municipal and industrial WWTPs in Sweden, large quantities of heat and bio-energy are recovered from sewage and wastewater. Anaerobic processes in some WWTPs are generating CH_4 for the production of heat, electricity, vehicle fuels, and local gas distribution networks. Around 35.8% of the produced biogas in Sweden in 2017 was generated by WWTPs (NIR Sweden, 2019).

NIR Sweden 2019 suggests that the biogas production at municipal WWTPs (anaerobic digestion of sludge) increased by 34.78% from 2005 to 2017 which about 11.0 % of the biogas was flared and 61.0 % was upgraded into fuel for vehicles in 2017.

2.2.2 Gryaab AB company profile

In Gothenburg in Sweden, the municipally-owned company is called Gryaab AB which is responsible for high water quality in local lakes, rivers, and the sea by cleaning wastewater from their owner municipalities. The company operates one of the largest WWTPs in the Nordic countries, Rya WWTP. By the 1960s the municipalities of the region joined to establish Rya WWTP with the aim of wastewater-free lakes and small watercourse by diverting the wastewater to a major tunnel system ending up at the Rya WWTP. The Rya WWTP was started to operate in 1972 (Gryaab, A.B., 2010). At the Rya WWTP, wastewater from their owner municipalities is treated, as well as the residual sludge product. Biogas is produced from the sludge and upgraded to vehicle fuel. (Gryaab, A.B., 2010)

Water purification happens at Rya WWTP and a large fraction of eutrophic compounds are removed from the wastewater and then returned to the cycle in the form of biogas and sludge. In the end, the purified water is released into the Göta River.

According to the direct translation of official Gryaab Environmental Policies, Rya WWTP improves and strengthens the positive environmental impacts of their operations and reduces their environmental impact through:

- ✓ Attempting to comply with applicable laws, environmental permits, and binding requirements and conducting environmental activities under the board's alignment documents, policies, and action plans.
- ✓ Contributing to an improved recycling of nutrients by producing Revaq certified sewage sludge for agriculture.
- ✓ Attempting to take advantage of the energy content of the wastewater.
- ✓ Minimizing emissions of pollutants to water, air, and soil.
- ✓ Limiting the supply of additional water and environmentally harmful substances and monitoring their levels and trends in wastewater and sludge.
- ✓ Taking the environment into account from a life cycle perspective when purchasing goods and services.
- ✓ Taking energy and resource consumption into account for major investments to improve resource efficiency and environmental performance.
- ✓ Striving to be a leading wastewater treatment company with positive development for users, employees, and the environment.

The wastewater treatment processes in Rya WWTP are briefly as follows:

Coarse bar screen (screening): The water from households and industries flows into pipes then ends up in the Rya WWTP tunnel system, which is about 13 km long. Since the tunnels are inclined, the water can naturally flow to the treatment plant. When the wastewater reaches the Rya WWTP, it is about 20 meters below the ground. Here the water is allowed to run through a mechanical grating which is 20 millimeters between the grid rods. In this part, the larger fraction from wastewater such as paper towels and other debris will remove within a 2 cm screen. This phase in treatment plant is called purification. Every day, just over 2 tons of these stuffs come to the Rya WWTP, completely unnecessary. The cleaning that comes to us is pressed and atomized and then burned and turned into electricity and heat. After the water has passed the coarse grids, the water is pumped up to ground level (Gryaab, A.B., 2010).

Sand Trap: In this phase, sand and gravel will sink to the bottom to stop entry to the plant and damage pumps and machinery (Gryaab, A.B., 2010).

Fine bar screens: In this section, the screen is 2 mm so the smaller particles will remove and be incinerated as a waste (Gryaab, A.B., 2010).

Primary setting: In this phase, the heavier particles will sink to the bottom and form the sludge which is going to be treated. Fat is lighter so it will float to the surface and it can be easily removed (Gryaab, A.B., 2010).

Add Iron Sulfate: To remove autotrophic P the ferrous sulfate is added. The iron sulfate causes the dissolved P is precipitated and form flocks. Later in the process, the flocks are bound in the sludge and sink to the bottom are then removed (Gryaab, A.B., 2010).

Activated sludge: Nitrifying and denitrifying bacteria prefer aerobic and non-aerobic conditions, respectively. Because of that, alternating zones of air blown into the basin from beneath and non-aerated zones are created in a so-called activated sludge process (Pell and Wörman, 2008).

Secondary settling: In this phase, bacteria and precipitated P sink to the bottom and form sludge. Since the sludge contains bacteria that purify the water, most of it is pumped back to the activated sludge basins (Gryaab, A.B., 2010).

Trickling filters: This is the area where bacteria grow on blocks of corrugated plastic sheets. When the water flows over the bacteria, ammonia is transformed into NO_3^-. In this phase, the first part of N will be removed through nitrification (Gryaab, A.B., 2010).

Post denitrification: The second phase of N removal will happen in this phase by bacteria which transform NO_3^- into N (Gryaab, A.B., 2010).

Disc filters: In this step, the small particles (larger than 0.015 mm) will be removed from the water (Gryaab, A.B., 2010).

Release: The treated water will be released into the lakes, rivers, or sea. (Gryaab, A.B., 2010).

3 Methods and materials

Some literature reviews were conducted via Google Scholar website, Web of Science, and an online search engine of the Gothenburg University Library. The same abstract keywords used through searching motors. Some reports and documents from the IPCC and NIR of Sweden were studied. Some technical definitions have been retrieved from Wikipedia, ScienceDirect.com, and Oxford Dictionary of Environment & Conservation.

3.1 Principle of Life Cycle Assessment (LCA)

The life cycle of a product or service includes all functions from the extraction of raw materials to production, construction, transportation, consumption, maintenance, and finally recycling and, disposal. LCA is an organized method to evaluate potential environmental impacts throughout the parts or the whole life cycle of a product or a service. Impact assessment can implement through quantifying the used resources and produced emissions (EC-JRC-IES 2010b). LCA is a supportive tool that can bring environmental outlooks into decision-making developments with the aim of more environmentally friendly products or identifying environmental indicators and how to measure them. Moreover, it can also be useful in marketing as environmental aspects are becoming more and more important for consumers (Antikainen 2010).

3.2 Life Cycle Assessment or Carbon Footprint

According to the ISO 1404 and 14044 standards, four major phases of LCA are as follows:

1) Defining the goal and scope for the assessment
2) Collecting life cycle inventory (LCI) for the process
3) Life cycle impact assessment (LCIA)
4) Interpreting the results

Some multi-methods can be used in LCA depends on the goal and scope of assessment. For instance, LCA only can include an LCI phase, or just one impact category such as CF, GWP or it may cover many impact categories.

3.2.1 Carbon Footprint Calculation Tool (CFCT)

In this master thesis only one impact category ‘’Carbon Footprint’’ was studied and conducted with an MS Excel spreadsheet (CFCT, 2014). The tool has been developed to increase knowledge about the climate impact of an individual WWTP and specify which of the WWT processes that have a large impact. In the end, the improvement strategies can be created based on the results from this tool. A further purpose of this tool is a comparison outlook among other WWTPs.

The Excel spreadsheets CFCT for calculating the climate impact from WWTPs consists of 13 sheets. The sheets are divided into four different groups:

Group 1: Inputs
Group 2: Results & Detailed Results
Group 3: EFs, Production of chemicals, GWP, Equivalence factors
Group 4: Input references and tables

There are some sheets allocated for inputs and relevant data was collected from operational sectors at Rya WWTP for the year 2019 and it calculates CFs for all functions contributing to emissions. The input data was classified into five categories like WWT, Chemicals, Energy, Transport, and Sludge and Waste. Some parts of the input sheets could be filled as well as leave vacant by an individual user based on their specific treatment methods at WWTP. Furthermore, the user will have an opportunity to add climate impact for the consumed chemicals in an individual sheet (production of chemicals). CFCT is a user-friendly tool that the user can choose or add definite alternatives for the treatment which are created at the plants. The options that are included in the tool are related to the most common handling practices of the Swedish WWTPs.

CFs are visible in the results and they are grouped into eight functions like WWT, Energy use, Biogas production and use, Screening and sand, Chemicals, Sludge treatment and use, Transports, and Recipients. Results were calculated in CO_2e which illustrates their GWP (IPCC, 2013). The GWP 34 and 298 kg CO_2e/kg CH_4, N_2O in 100 years-time horizon was used for CH_4 and nitrous oxide, respectively. The CF of the whole plant was presented with the parameters like total incoming BOD, COD, N, and P.

The approach of this project is an empirical model that is feasible for calculating the total CF of the whole WWTP including the three major GHG emissions like CO_2, CH_4, and N_2O as proposed in (IPCC 2006; IPCC, 2019). It is possible to choose among some EFs from literature to carry out a sensitivity analysis.

EFs and GWPs were taken from literature and references listed on the final sheets and updated in this work. The climate impacts of chemical production were received from chemicals suppliers and the model was updated according to the new values. Following clauses was asked via correspondences with chemicals suppliers:

- Climate Impact via chemical production (CO_2e kg/Ton)
- Energy consumption for chemical production
- Overall Impact Assessment
- Transportation of chemicals included/excluded
- Sort of fuel used in transportation
- Transportation distance

In this study, the total CF of Rya WWTP in 2019 has been updated and compared with the footprint of 2018 and discussed. All contributors to the CF for the whole WWT plant and processes were presented in the result and discussion section. Then, conclusions were stated and improvement strategies have suggested.

3.2.2 System boundary

Generally, a system boundary refers to a dividing line between a system and its environment. Within the LCA methodology, the system boundary is the dividing line between the factors that are included and taken into account in the environmental assessment and those that be left outside and disregarded. The result of the study depends on how system boundaries are defined. The system boundaries used in the calculation tool is described in figure 2.

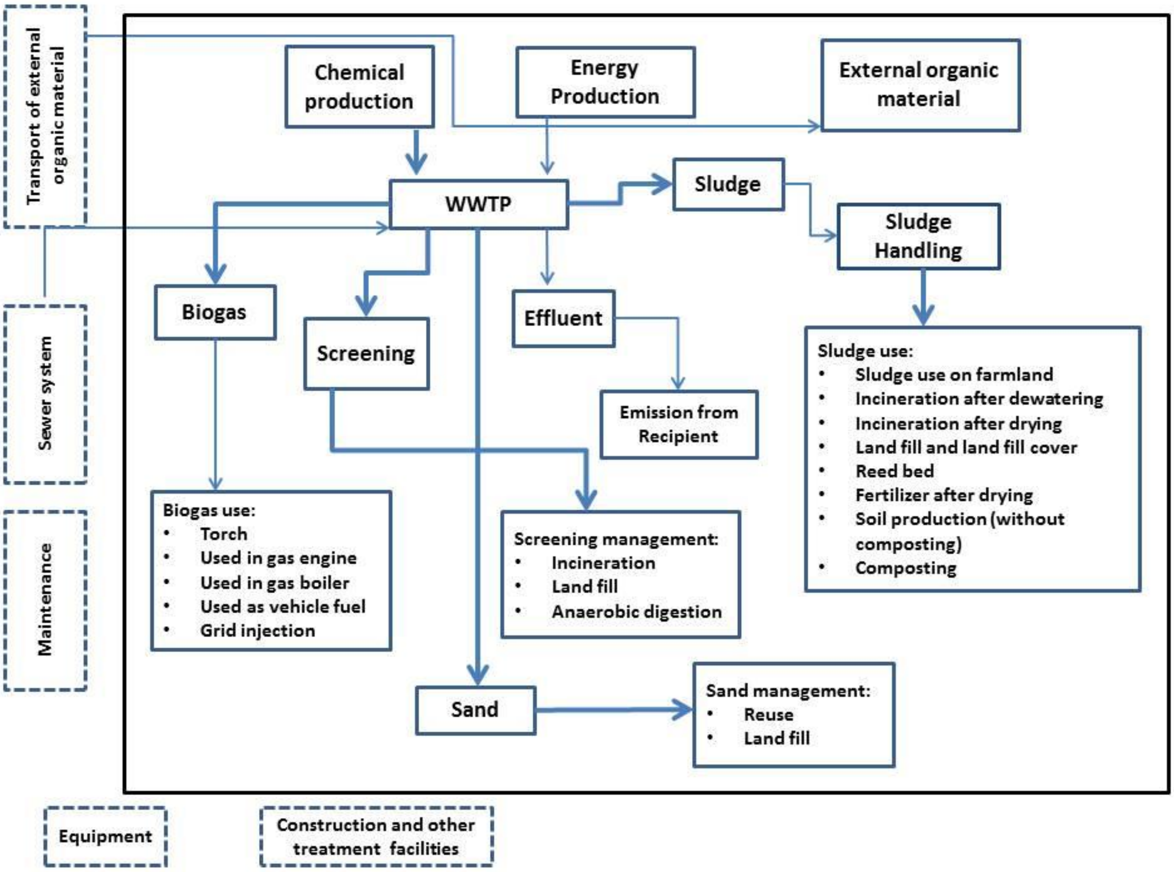


Figure 2. System boundary. Dashed boxes indicate the processes of which emissions have not considered in CFCT. Thick arrows represent the transport of materials.

3.2.3 Functional Unit (FU)

The FU is used as a reference unit according to which inputs and outputs are normalized (Antikainen, 2010). For example, a certain volume of influent wastewater can be a FU. When LCA is used for comparing different choices then the FU can use as a reference unit (Guereca *et al*. 2019). The same FU allow meaningful comparisons on a common basis. In a comparative study, the selected FU must be the same in all compared systems. An example of this is that 0.25 kg of plastic and 0.5 kg of glass can be comparable FU if both used as beverage packaging to store and transport 5 liter of beverage, and the FU is expressed as a "packaging of 5 liters of beverage".

About wastewater treatment, there are several different ways of defining the FU, for instance:

- Population equivalents (PE) / in Sweden is 70 g BOD_7 person $^{-1}$day^{-1}
- Flow (m^3)
- Separation of a specific amount of N, P or COD
- A load of a specific amount of N, P or COD

The FU kg CO_2e / person, year is used in this master thesis.

3.2.4 Uncertainty analysis

In the final stage, the results obtained from the LCIA had gathered and analyzed according to the goal and scope of the study. It was important to identify the most relevant data and analyze their accuracy; sensitivity and coherency to the study. In this part, the quality of the different values for some parameters was analyzed to see the possible variance in the results. Uncertainty analysis estimates how much the result sensitive to the value of that parameter.

4 Results and discussion

4.1 Total Carbon Footprint

The CF of eight sectors in Rya WWTP was calculated by using the CFCT model. The CF was quantified based on CO_2e. The results from CFCT have been evaluated to determine the processes that contributed most to the total CF.

Table 3. Total carbon footprint for Rya WWTP in years 2018 and 2019.

Year	Total carbon footprint (ton CO_2e / year)	Total carbon footprint (kg CO_2e / person, year)
2018	13,574	17.4
2019	13,333	16.9

The FU for comparing the CF of WWTP in 2019 and 2018 is the total annual produced CO_2e per person. The CF in 2019 was about 3.4% lower than in 2018.

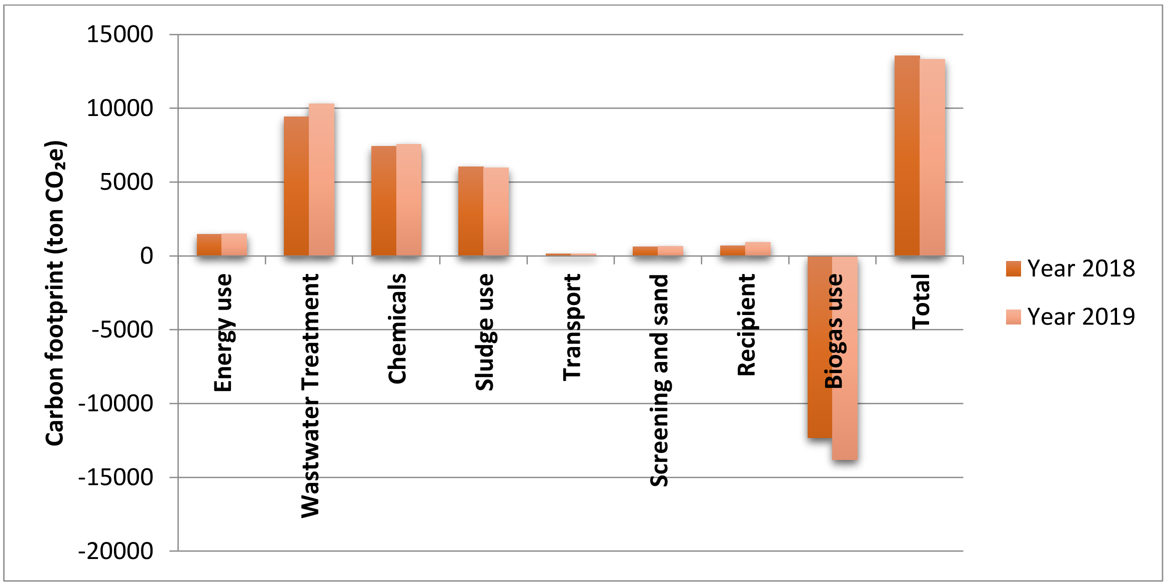


Figure 3. Total carbon footprint in eight sectors from Rya WWTP in 2018 and 2019

According to figure 3, the WWT process had the largest contribution in total CF in Rya WWTP in both years 2018 and 2019. The second contributor was related to chemical production and the third one was accounted for sludge use and sludge handling process. The other sectors had minor contributions to the total CF in Rya WWTP.

The detailed results about the major and minor contributors to the rising total CF in Rya WWTP were discussed in bellow sub-divisions.

4.2 Energy use

The total value for CF in the energy sector in Rya WWTP is a sum of Electricity use-purchased, Electricity use-production, Heat, and Cooling (Table 4). The CF in this sector was calculated based on the local EFs for energy. Regional EFs have been updated in the CF calculation tool.

Table 4. Carbon footprint of the energy sector from Rya WWTP in 2018 & 2019.

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Electricity use-Purchased	534	524
Electricity use - Internal production	0.51	0.77
Heat	949	972
Cooling	0	0
Total Carbon footprint (ton CO_2e)	**1,484**	**1,496**

The CF in the energy sector has risen by about 1% in 2019 due to a bit higher heat consumption.

4.2.1 Electricity

Majorly, the Rya WWTP purchases electricity from the market, and some electricity are also produced at the plant by solar panels. The energy bought was produced by wind and all the electricity utilized at Rya WWTP can thus be counted as green energy. Following the CF reduction objectives, Rya WWTP has facilitated internal electricity production via solar panels in 2018 and 2019. Production of renewable electricity via solar panels caused to raise energy neutrality at Rya WWTP.

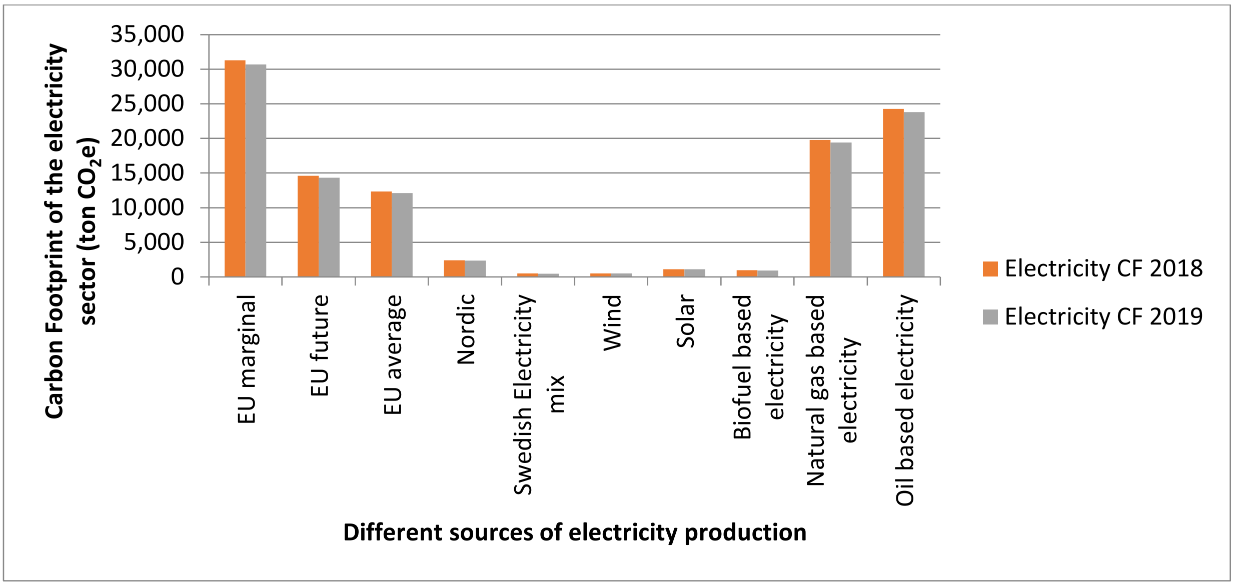


Figure 4. The impact of different energy emission factors (EFs) on electricity carbon footprint (CF) at Rya WWTP, 2018 and 2019

The sensitivity of using different sources of electricity and their impact on total CF of electricity in the years 2018 and 2019 were analyzed (Figure 4). According to the analysis, if the source of electricity used in Rya WWTP was non-renewable, the CF of this sector would increase substantially. The CF of wind source electricity with the least GHG emissions is the best scenario for Rya WWTP.

4.2.2 Heat

Rya WWTP already has access to the local heating source with a low EF. The CF for heat in Rya WWTP calculated with the local EFs 75 ton/GWh in 2019 and 73 ton/GWh in 2018. If they utilize natural gas or oil-based heating sources (non-renewable sources) with high EFs the CF of the heat sector will increase substantially (Figure 5).

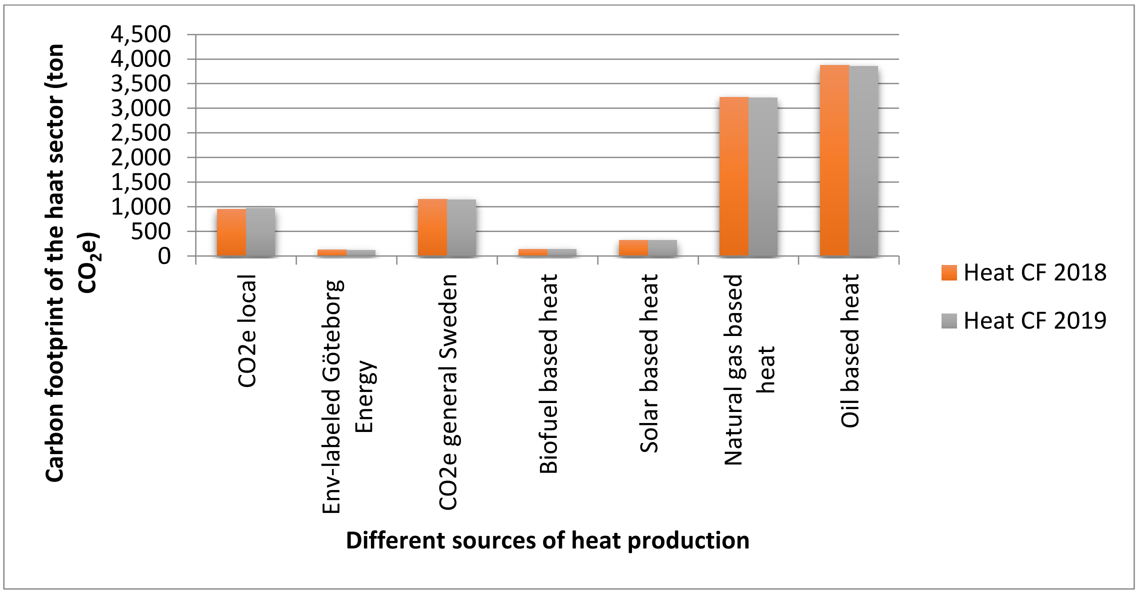


Figure 5. Sensitivity of different emission factors (EFs) and their impact on heat carbon footprint (CF) in Rya WWTP 2018 and 2019

4.3 Wastewater treatment

Based on the literature review, wastewater treatment processes hold a large contribution to the total CF in a WWTP (Gustavsson, Tumlin, 2013). N_2O emission via biological nutrient removal (BNR) can in some cases, correspond to almost half of the CF in the WWTPs (Maktabifard *et al*., 2019).

The findings have been confirmed in this project. The direct emissions from the WWT sector was accounted for the major amount of direct N_2O and CH_4 emissions through both wastewater treatment and sludge treatment process, respectively (Section 4.4). The measured N_2O and CH_4 emissions from sludge liquor treatment are also included in the site-specific measurement of N_2O and CH_4 at Rya WWTP.

According to the site-specific operational data in CFCT (Input WWT), about 96% of the N_2O was emitted via the wastewater treatment process, and about 80% of CH_4 was emitted through the sludge treatment process (Section 4.4). Most of the measurements of N_2O and CH_4 have been carried out in the year 2014-2015 and only the site-specific N_2O emissions from the wastewater treatment process have been measured and updated in 2018 and 2019. For this reason, the same value has been used for years 2018 and 2019 (Table 5 and Table 10).

The measured CF values are generated by multiplying the measured amount with respective GWP-value (Table 6).

Table 5. Measured site-specific data in wastewater treatment in Rya WWTP

Site specific data - water treatment	**2018/ton**	**2019/ton**
Measured CH_4 emissions	36.16	36.16
Measured N_2O emissions	27.56	30.47

Table 6. The Carbon footprint of the WWT process in Rya WWTP in 2018 & 2019

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Measured emissions (CH_4)	1,229	1,229
Measured emissions (N_2O)	8,213	9,080
Total Carbon footprint (ton CO_2e)	9,442	10,310

Table 6 declares that the CF of the WWT process is higher by 9% in 2019 due to rising higher levels of direct N_2O emissions.

Commonly, N_2O and CH_4 emission measurements are a challenging process specifically at open WWTPs (Yoshida *et al.*, 2014). Otherwise, measurements in the underground WWTPs like Viikinmaki WWTP in Finland are much more feasible (Blomberg *et al.*, 2018). Therefore not all the WWTPs perform site-specific measurements. Since, literature data for N_2O direct emissions from WWT processes is included in the CFCT; plants without their measurements can still use the model. The calculated emissions of N_2O and CH_4 have been defined by using EFs from literature. A sensitivity analysis testing different EFs for N_2O is presented in 4.3.1 below. At Rya WWTP the theoretical values (calculated emissions) for N_2O EFs are not being used as the Rya WWTP is monitoring the measurements annually.

4.3.1 Sensitivity analysis varying the EFs of direct N_2O emissions

In the base scenario in the tool, measured data from Rya WWTP has been used. However, those values are based on a limited number of measurements, during a rather short time interval. The EFs for N_2O from the wastewater treatment varies quite substantially in the literature. For those reasons, the effects of testing different N_2O EFs from literature are analyzed in this paragraph.

There is considerable variability in the N_2O EFs which determines direct emission of N_2O due to site-specific matter. The EF of 0.0157 kg N_2O /kg N denitrified (Foley *et al.*, 2010) was used as a reference value in this model. But, a broad range of EFs values has been reported in the literature (table 7). EFs of N_2O have been listed in table 7 and the effect of direct N_2O emissions on the CF for different EFs N_2O is shown in table 8. The N_2O EFs from site-measurement of Rya WWTP was translated to the same unit and added to table 7.

The different reported values for the N_2O EFs is referring to the differences technologies in WWTPs and processes situations, and numerous methodologies used for the monitoring methods (Maktabifard *et, al*., 2020).

Table 7. N_2O EFs in full-scale Domestic WWTPs-(IPCC, 2019) (Rya WWTP site-measurement). All data come from biological nitrogen removal (BNR) process

Items	Type of treatment process [1]	N_2O EFs (kg N_2O -N/kg N)	References
1	OD	0.00016	(Masuda *et al.* 2018)
2	CAS	0.00036	(Aboobakar *et al*. 2013)
3	AO	0.0013	(Masuda *et al*. 2018)
4	Not available	0.0076	Rya WWTP site-measurement (2018)
5	Not available	0.0080	Rya WWTP site-measurement (2019)
6	OD	0.0080	(Foley *et al.* 2010)
7	EA	0.0157	(Foley *et al.* 2010)
8	AO	0.021	(Foley *et al.* 2010)
9	SBR	0.029	(Bao *et al.* 2016)
10	SBR	0.038	(Rodriguez-Caballero *et al.* 2015)
11	AO	0.045	(Foley *et al.* 2010)
12	AO	0.12	(Rodriguez-Caballero *et al.* 2014)
[1] OD; Oxidation ditch, CAS; Conventional activated sludge process, AO; Anaerobic-oxic activated sludge process, EA; Extended aeration process, SBR; Sequencing batch reactor.			

Table 8. Effect of direct N_2O emissions on the total carbon footprint for different EFs N_2O

Range	EF N_2O (Uncertainty range) (kgN_2O/ kg $N_{denitrified}$)	Calculated Total CF of the WWTP (kg CO_2e/Person . year)	
		2018	2019
Low	0.00016	7.1	5.5
	0.00036	7.2	5.7
	0.0013	8.0	6.4
	0.0080	13.8	11.7
Mid	**0.0157**	**20.5**	**17.7**
	0.021	25.0	21.8
	0.029	31.9	28.0
	0.038	39.7	35.0
High	0.045	45.7	40.5
	0.12	101.3	98.9

First, the EFs of N_2O is a very important parameter for the total CF. But, there is an ongoing debate in literature about those values, since the measurements are by no means simple to carry out. Furthermore, it is not certain, that all those EFs are relevant for the Rya WWTP, due to differences in the applied wastewater treatment processes. However, it cannot be out ruled that other plants are more successful in optimizing the processes achieving low EFs for N_2O, considering the some of the low EFs, in table 7 and 8. Thus, Rya WWTP should continue with the measurements of N_2O, to improve knowledge about the site-specific N_2O emissions. It would also be welcome, with more continues measurements, so that more full-scale experiments could be carried out, optimizing the process parameters for lower N_2O-emissions. Rya WWTP should also continue to contribute and closely follow the discussions in the literature.

In one study, long term monitoring campaign and quantifying full-scale N_2O emission into seasonal pattern carried out and trend between N_2O emission and process conditions were proposed the dynamic N_2O emission. According to the study, relatively low/high N_2O emissions happened in seasons with a decreasing/increasing trend of water temperature, respectively (Chen *et al.*, 2019).

The study declared that incomplete denitrification in the anoxic phase might potentially cause to emit more N_2O due to the competition among different denitrification steps for electron donors consequently; proper extension the length of anoxic phase could be a potential mitigation method to regulate N_2O emission (Chen *et al.*, 2019).

4.4 Sludge treatment and sludge use

The CF of the sludge treatment and sludge use are considered in this sector. The total CF has arisen from measured emission from sludge processes, sludge storage, carbon sequestration, and sludge handling including landfill, incineration of sludge, reed bed, etc. The contributions of the mentioned sectors to the total CF of sludge treatment has stated and compared in both years 2018 and 2019 (Table 9).

According to table 9, the total CF reduction for sludge treatment and use was negligible about 1% in 2019. The major contributor to the total CF in this sector is related to the sludge process. Sludge storage was about 148 tons CO_2e higher in 2019. Sludge handling was reduced at a minor level by about 6.6% in 2019.

Table 9. Carbon footprint of sludge treatment in Rya WWTP in years 2018 & 2019

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Measured emissions-sludge processes	5,295	5,295
Sludge storage	867	1,015
Sludge handling (sludge disposal practices)	966	906
Carbon sequestration	-1,082	-1233
Total Carbon footprint (ton CO_2e)	**6,046**	**5,983**

4.4.1 Sludge treatment process -Anaerobic digestion

The amount of emissions from sludge processes are generated by multiplying the measured amount with respective GWP-value (Table 10). In the CFCT results, the major contributor to the CF of the sludge treatment is CH_4 emissions from the anaerobic digestion.

Table 10. Measured site-specific data in sludge treatment process in Rya WWTP

Site specific data - sludge treatment	2018/ton	2019/ton
Measured CH_4 emissions	145.92	145.92
Measured N_2O emissions	1.12	1.12

According to the site-specific operational data in CFCT (Table 10) and (Table 7), about 80% of the total CH_4 emissions from Rya WWTP, is emitted through the sludge treatment process while only 3.7% of the N_2O emissions were emitted from that process. These measurements have been made in the years of 2014-2015 and were not updated for 2018 and 2019.

4.4.2 Sludge storage

Table 11 suggests that a major amount of the GHG emissions from the sludge storage is accounted for the CH_4. CF of sludge storage is about 14% higher in 2019 compared with 2018. Sludge was stored for 99 days in 2018 and 105 days in 2019 in Rya WWTP. Studies suggest that there is a correlation between the storage time and the amount of direct emission of CH_4 (Gustavsson and Tumlin, 2013).

Table 11. Carbon footprint of sludge storage in Rya WWTP in 2018 & 2019

Items	2018 (ton CO_2e)	2019 (ton CO_2e)
N_2O-emissions from sludge storage before use	1.83	2.18
CH_4-emissions from sludge storage before use	9.42	10.75
Total Carbon footprint (ton CO_2e)	867	1015

4.4.3 Sludge disposal practices

The amount of emission in this sector depends on the sort of sludge disposal practices are used in a WWTP. At Rya WWTP, the compost fraction and solid waste from screening (100%) are using in soil production and incineration, respectively in both years.

The shares of different scenarios of sludge handling at Rya WWTP are stated in table 12. Emission from sludge handling has been reduced by about 6.6% in 2019 compared with the year before (2018) due to a bit higher ratio of sludge used on farmland (Table 9). The digested sludge could be used on farmland as a fertilizer as it contains valuable nutrients like N and P. To avoid transmittance of pathogenic microorganism, the sludge has to be treated.

Table 12. Shares of sort of sludge handling at Rya WWTP year 2018 and 2019.

Sludge use	2018	2019
Sludge used on farmland	55%	58%
Soil production (without composting)	0%	2%
Composting	45%	40%

4.5 Biogas production and use

Biogas production is a sustainable method for energy balance used at Rya WWTP. There are several analyses which have been carried out for CF reduction by improving the energy balance from wastewater (Chen *et al.*, 2019; Gu *et al.*, 2016; Mamais *et al*., 2015; Sun *et al*., 2017; Sweetapple *et al*.,2015; Wang *et al.*, 2016).

Rya WWTP produces about 70 GWh of biogas annually. The biogas is converted into eco-labeled vehicle fuel. The produced biogas by Rya WWTP in a year can supply 5,000 passenger cars. Biogas consists of two-thirds of CH_4 gas. The sludge is digested in Rya WWTP biogas facilities which cause the organic matter to break down and form biogas. (Gryaab, A.B., 2010).

In order to increase the biogas production, Rya WWTP receives leftovers from restaurants and these food wastes are then added to the anaerobic digestion process. The produced biogas is sold to Gothenburg Energy for upgrading to 95-98% CH_4 gas and the gas is sold as a vehicle fuel. The annual biogas produced by Rya WWTP is enough for a car to drive 2,700 tours around the earth.

The total CF value for biogas use is the sum of external use of biogas, biogas emissions, biogas use, and distribution as well as N_2O and CH_4 from biogas use (Table 13).

Table 13. Carbon footprint of biogas use in Rya WWTP in 2018 & 2019

Items	2018 (ton CO_2e)	2019 (ton CO_2e)
External use of biogas	-17,598	-18,433
Biogas emissions	259	133
Biogas use and distribution	4,807	4,317
N_2O and CH_4 from biogas use	211	196
Total Carbon footprint (ton CO_2e)	**-12,321**	**-13,787**

According to table 13, the CF in biogas use has decreased by 12% in 2019 which means a positive climate impact at Rya WWTP, consequently.

The CF for biogas use in the CFCT model applied to Rya WWTP is minus. This shows that biogas production can have a great positive effect on the climate impact for WWTPs. The minus effect in CF means that the net energy production through the biogas within the system boundaries (inside the WWTPs) is positive. This energy is assumed to be renewable and substitutes the traditional sources of energy such as fossil fuels (natural gas, petrol, etc.). The difference in the CF of biogas and fossil fuels would lead to a minus CF.

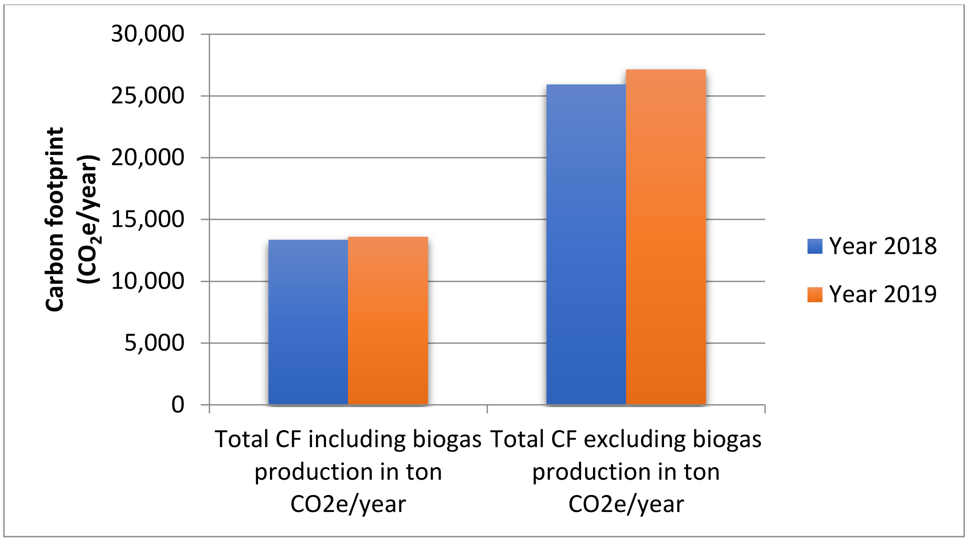


Figure 6. Total Carbon footprint with and without biogas production at Rya WWTP in 2018 and 2019

According to figure 6, the total CF will be double without biogas production at Rya WWTP which approves the concept the biogas production, could be a potential and sustainable method for energy balance in a WWTP.

4.6 Chemicals

Normally, some specific chemicals are utilized in the treatment processes in a WWTP. The production of the chemicals generates substantial amounts of indirect GHGs. In this model, the climate impact of chemical production is evaluated. Climate data for the most commonly added chemicals are included in the CFCT model, such as Fe (II) compounds, flocculants of different types, and methanol as a carbon source. However, it is straightforward for individual CFCT-users to add data for other chemical compounds. Transportation of chemicals (finished products) from the wholesaler’s warehouse to the WWTP is added to the transport part of the CFCT-model.

4.6.1 Climate Impact from chemical production

In this project, the list of purchased and utilized chemicals in Rya WWT processes was received from the purchasing department and the climate impact through chemical production (1 kg CO_2 per production of 1-ton chemical) was asked for from suppliers and manufacturers (Table 16). The CF transportation of chemicals is included in the transportation parts of the CFCT model. The sustainability reports or impact assessment report of the supplier was asked for in the same email that asked for the climate impact of the chemicals. The CFCT have updated according to the new climate impact values (kg CO_2e /ton).

The CF of each chemical was taken by multiplying the climate impact of a chemical (kg CO_2e/ton) to the number of utilized chemicals in the treatment process. Among used chemicals, the methanol is transformed into CO_2 by the respiration of organisms in the treatment process, because of that the CF of the respiration of the methanol is added to the total CF of chemicals (Table 15). The EF of fossil methanol has been updated, and the new value is about half of the old value. This has a reasonably large impact on the total CF, about a 15 % decrease (Table 16).

The indirect GHG emissions from chemicals production have a second contribution in total CF in this study in both years 2018 and 2019 (Figures 3). Among them, the carbon source chemicals have the highest contribution in total CF of chemical in Rya WWTP (Table 15) due to utilizing extra carbon source chemicals to facilitate N removal in the denitrification process.

Table 15. Carbon footprint of used chemicals in Rya WWTP in years 2018 & 2019

Items	**CF 2018 (ton CO_2e)**	**CF 2019 (ton CO_2e)**
Carbon source chemicals	2127	2017
Coagulants	925	845
PAC (Poly Aluminum Chloride)	130	502
Polymers	655	797
Respiration (Methanol)	2,871	2,770
Other chemicals	732	651
Total carbon footprint (ton CO_2e)	**7,440**	**7,582**

Table 16. Climate impact of used chemicals in Rya WWTP.

Chemical list	**Suppliers**	**Climate impact (kg CO_2e/ton)**
Ekoflock 90	Feralco Nordic AB	536
PAX-XL100	Kemira Oyj	555
Quickfloc ($FeSO_4$)	Kronos Titan AS	303
Zetag 4125 Zetag 8180 Zetag 7557	BTC Europe	2260
Methanol	Helm Skandinavien	1000 (Methanol Fuels, n.d)
Defoamers	Citru-Ren kemikalier	Not available
Phosphoric acid 75 %	Helm Skandinavien	1417
Sodium hypochlorite 12% (NaClO)	Univar solution	890
Sodium hypochlorite 6% (NaClO)	Univar solution	890
Nitric acid (HNO_3)	Univar solution	551

4.6.2 Sensitivity analysis varying climate impact values for chemical production

Because of the high-level consumption of methanol in Rya WWTP in both years 2018 and 2019, the sensitivity of climate impact of fossil-based, fossil-free methanol and bio-methanol and their impact on total CF of chemicals have been analyzed.

Table 17 and figure 8 declare that fossil-free methanol has a lower level of climate impact instead of fossil source methanol in total CF of chemicals in Rya WWTP in 2019 and 2018. Using fossil-free methanol potentially could be the improvement strategies for CF mitigation.

Table 17. Climate impact of fossil and non-fossil based methanol

Items	Climate impact (kg CO_2e/ton)	Carbon footprint chemical-2018 (ton CO_2e)	Carbon footprint chemical-2019 (ton CO_2e)
Fossil source methanol	1000	7,440	7,582
Fossil free methanol	150	5,664	5,868
Bio-methanol	760	6,939	7,098

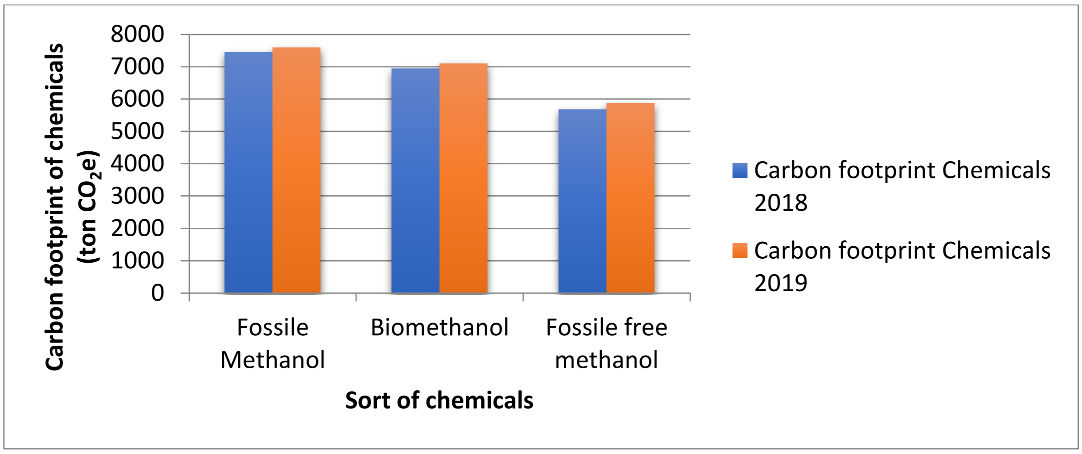


Figure 7. Sensitivity analysis of fossil based, fossil free methanol and bio-methanol and their impact on total carbon footprint (CF) of chemical at Rya WWTP in 2018 and 2019

4.7 Transport

The CF in this sector is generated by a formula including input data (distance from suppliers to Rya WWTP (km), fuel consumption), and EFs of vehicle fuels.

Fossil fuel combustion that comes from the transportation of bio-solids is an important source of emissions (IPCC, 2006), whereas emissions from that sector at Rya WWTP were at a low level. According to the table 18, the CF of transport for Rya WWTP had a minor contribution to the total CF, and no significant difference between CF of 2018 and 2019 was observed. The reason for the low CF is mainly caused by the usage of HVO-diesel (Hydrogenated Vegetable Oil) for their transport activities. HVO is a form of biodiesel. The default EFs values in the transportation sector in Rya WWTP are 1.170 kg CO_2e/10 km (HVO truck 40 ton) and 1.755 kg CO_2e/10 km (HVO truck 60 ton).

Table 18. CF of transport in Rya WWTP in 2018 and 2019.

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Chemicals	136	139
Sludge to storage	26.77	26.25
Sludge to farmland	0	0
Sludge to incineration	0	0
Sludge to composting facility	0.29	0.23
Sludge to soil production landfill/ landfill cover	0	0
Screening	0.11	0.13
Sand	0	0
Use of compost	0	0
Ashes	0	0
Biogas (not grid injection)	0	0
Total carbon footprint (ton CO_2e)	**164**	**165**

HVO is one of the alternative and renewable diesels that have been developed with a low level of climate impact. HVO is a sustainable fuel that can produce up to 90% lower GHG emissions.

4.8 Recipient

The end-stage of the purification of wastewater at Rya WWTP is discharging the water to the aquatic ecosystem. The total CF in this sector includes N_2O and CH_4 emissions from the recipient (river, lake, estuary, or sea).

According to the CFCT, the amount of N in outgoing wastewater (effluent) determines the N_2O emission in the recipient. Total N in effluent wastewater was 730 and 1000 tons/year in 2018 and 2019, respectively. The amount of CH_4 emission in the effluent is determined by the amount of total BOD_7 and COD in the effluent wastewater. The CH_4 emission was not measured in this sector at Rya WWTP and is assumed to be zero.

Table 19. Carbon footprint of the recipient in Rya WWTP in 2018 & 2019

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Sea N_2O	683	936
Sea CH_4	0	0
Fresh water recipient N_2O	0	0
Fresh water recipient CH_4	0	0
Total carbon footprint (ton CO_2e)	**683**	**936**

Table 19 shows that the CF in 2019 has raised about 37% in 2019 majorly due to the larger amount of N_2O emission.

The dissolved CH_4 and N_2O in treated wastewater (effluent) potentially can release (Short *et al.* 2014; Short *et al.* 2017). Study shows that there is a strong correlation between the condition of the aquatic environment and the generation rate of CH_4 and N_2O (Smith *et al*. 2017). If the water bodies where the effluent discharged to be more eutrophic, the additional organic matter in discharged wastewater will increase. Many aquatic environments which are naturally eutrophic, whereas others have been altered by human activities such as using more soil fertilizer or discharging wastewater and subject to eutrophication, consequently.

4.9 Sand and Screening

In the mechanical phase of the treatment process at WWTPs, there are some by-products like sand and solid particles that need to be recycled. The screening materials are normally sent to Renova in Gothenburg for incineration, to produce heat and electricity. The contributors to the total CF in this sector are mentioned in Table 20.

Table 20. Carbon footprint (CF) of sand and screening sector in Rya WWTP in 2018 & 2019

Items	**2018 (ton CO_2e)**	**2019 (ton CO_2e)**
Total energy production from incineration of screenings	638	648
Sand	0	0
Total carbon footprint (ton CO_2e)	**638**	**648**

According to table 20, there were minor differences among CF 2018 and 2019. The CF has increased by only 1.5% in 2019.

5 Conclusions

Rya WWTP protects the environment by reducing the sewage nutrient load in the aquatic environment. However, it also has an impact on the environment by emitting GHGs into the atmosphere.

According to the research questions of this master thesis, climate impact from Rya WWTP has been estimated via the CF assessment tool. Also, the substantial contributors to the climate impact and possible ways of mitigating CF were recognized. Moreover, the sensitivity of the different EFs and possible impact on results was analyzed.

The major contribution to the total CF was direct emissions of N_2O in WWTP processes from Rya WWTP for both years 2018 and 2019. The second contributor was related to indirect GHG emissions from the production of chemicals. The direct emission of CH_4 to the atmosphere through sludge treatment processes (anaerobic digestion) accounted for the third major contributor to the total CF. CF of the sludge storage was increased by 14 % from 2018 to 2019, due to a longer average storage time.

The major resources used in Rya WWTP are electricity, heat and, process chemicals. Moreover, fuel is needed for transportation. Majorly, the Rya WWTP purchasing electricity with renewable sources with low climate impact, mainly wind power. Also, they have installed some solar panels for electricity production. The energy bought was produced with renewable sources and all the electricity utilized at Rya WWTP can be counted as green energy with low climate impact. Rya WWTP was using the local district heating source with low EFs; 75 ton/GWh in 2019 and 73 ton/GWh in 2018.

The EF of fossil methanol has been updated, and the new value is about half of the old value. This has a reasonably large impact on the total CF, about a 15 % decrease.

The total CF will be doubled without biogas production at Rya WWTP. The CF for biogas production and use is minus because biogas can replace some fossil gas, and thus this could be regarded as a negative contribution to the CF.

The CF of transport in Rya WWTP had a negligible contribution to the total CF due to utilizing fossil-free fuels in transportation systems.

6 What Rya WWTP can do to decrease CF?

- One potential opportunity for the Rya WWTP is purchasing environmentally labeled district heating, since the other good heat sources like bio-based goes with a major investment, and probably not a cost-efficient way forward.

- Improvement of the processes for storage and handling of the sludge could yield a substantial decrease in CH_4 emissions. Among sludge disposal practices sludge use on farmland is recognized as the best scenario with less possibility of rising CH_4 emission than composting (Maktabifard *et al.*, 2020). Sludge storage in piles before farmland application potentially raises CF (Gustavsson and Tumlin, 2013). Consequently, minimizing sludge storage could be a potential mitigation method for CH_4 emissions.

- According to the long term monitoring campaign full-scale N_2O emission, incomplete denitrification in the anoxic phase might potentially cause larger emissions of N_2O due to the competition between different denitrification steps for electron donors. Consequently, the proper extension of the length of the anoxic phase could be a potential mitigation method to regulate N_2O emissions (Chen *et al.*, 2019).

- Following the strategic development target for the reduction of indirect CF of chemicals, Rya WWTP is already negotiating with chemicals suppliers to purchase the cost-efficient chemicals with less climate impact which could reduce the indirect CF substantially.

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