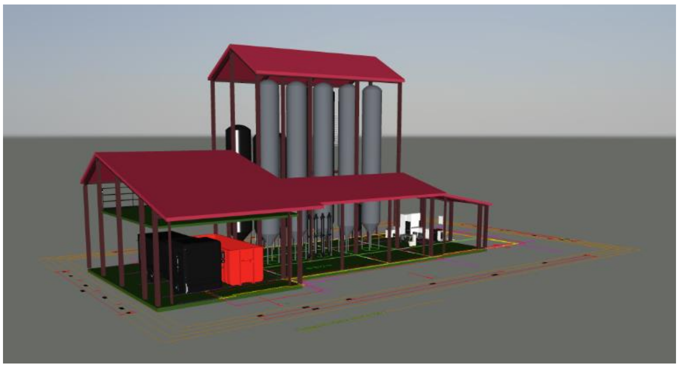
Master thesis Energy Science

# IDENTIFYING THE GREENHOUSE GAS REDUCTION POTENTIAL OF AUTOGENERATIVE HIGH PRESSURE DIGESTION

A comparison between the current scenario using Anaerobic Digestion and Autogenerative High Pressure Digestion in combination with an A-Trap for higher sludge recovery



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# Abstract

The mass and energy flows of the entire process of wastewater treatment, including the water-, sludge- and biogas line, are modelled in this research. This model is based on input data of the Wastewater Treatment Plant (WWTP) Amsterdam West. Connecting the entire system made it possible to make changes to the technologies within one part of the system, and to calculate the corresponding effect on the mass and energy flows of the entire system. This system model is used to provide input data for a consequential Life Cycle Assessment (cLCA) on the Global Warming Potential (GWP) of the WWTP Amsterdam West in combination with different technologies to capture and digest sludge. This cLCA includes biogenic carbon dioxide, in contrast to current practices in LCA, showing all emissions in wastewater treatment and indicating the remaining potential of Carbon Capture and Utilisation (CCU). Four scenarios are created, which differ from each other in the technologies used. First, a baseline scenario is created, which consists of the current technologies used at the WWTP Amsterdam west. The second scenario (A-trap scenario) consists of an A-trap instead of a Pre-Settling Tank (PST). An A-trap captures more sludge from the wastewater than a PST, resulting in a reduced sludge flow through the waterline and an increased sludge output towards the sludge line. The third scenario (AHPD scenario) consists, in addition to an A-trap, of Autogenerative High Pressure Digestion (AHPD) instead of Anaerobic Digestion (AD). AHPD is a new technology that directly produces biomethane with a methane content between 90% and 95% (Lindeboom et al., 2014). It is expected that the biomethane can be directly injected into the gas grid, in contrast to low calorific biogas from AD. The fourth scenario ($AH_2PD$ scenario) is like the AHPD scenario, but also includes the injection of hydrogen. This leads to the conversion of hydrogen and carbon dioxide into methane. The cLCA resulted in a total GWP for the entire WWTP Amsterdam West including biogenic $CO_2$ of $51*10^3$ tonne $CO_2$-eq per year for the baseline scenario. Compared to this scenario, the GHG reduction potential is 8% for the A-trap scenario, between 27% and 37% for the AHPD scenario and between 28% and 37% for the $AH_2PD$ scenario. The variance in the GHG reduction of the AHPD and $AH_2PD$ scenario is caused by uncertainty in the end-use of the digested sludge, which can be as a fertiliser or in a CHP.

# Executive summary

Global Greenhouse Gas (GHG) emissions have increased by more than 70% since 1970, leading to an increasing global temperature (Metz et al., 2007). Part of these (fossil) emissions are emitted by Wastewater Treatment Plants (WWTP's). The GHG emissions of WWTP's are particularly interesting since they emit GHG emissions because of their electricity and heat demand, but they also can reduce GHG emissions using the produced sludge (organic material) for biogenic energy production. Furthermore, biogenic $CO_2$ emitted in WWTP's can potentially be reduced using Carbon Capture and Utilisation (CCU).

The first goal of this research is to model the mass and energy flows of the entire process of wastewater treatment and to connect the water-, sludge- and biogas line. This connection is not made so far in literature. The connection between the entire system was made using mass allocation based on the Chemical Oxygen Demand (COD). Connecting the entire system made it possible to make changes to the technologies within one part of the system, and to calculate the corresponding effect on the mass and energy flows of the entire system. This model is used to provide input data for the second goal of this research, which is to quantify the Global Warming Potential (GWP) of different combinations of technologies used to capture and digest sewage sludge. Four scenarios are created, which differ from each other in the technologies used. These scenarios are based on input data from the WWTP Amsterdam West and are listed and explained underneath.

- **Baseline scenario**: This scenario consists of the current technologies, used at the WWTP Amsterdam west[1].
- **A-trap scenario**: This scenario differs from the baseline scenario since an A-trap[2] is installed instead of a Pre-Settling Tank (PST).
- **AHPD scenario**: This scenario consists, in addition to an A-trap, of Autogenerative High-Pressure Digestion[3] (AHPD) instead of Anaerobic Digestion (AD).
- **AH$_2$PD scenario**: This scenario is like the AHPD scenario, but also includes the injection of hydrogen. This increases the biomethane and surplus gas yields.

[1]The waterline consists of a PST, Aeration Tank (AT) and a (secondary) Settling Tank (ST). The sludge line consists of an AD, a centrifuge and a Combined Heat and Power (CHP) plant to burn the digested sludge. The low calorific biogas (60% methane) produced with AD, is burned for 87% in a CHP and 13% in a torch (Waternet, 2015).

[2]An A-trap captures more sludge from the wastewater than a PST, resulting in a reduced sludge flow through the waterline and an increased sludge output towards the sludge line.

[3]AHPD is developed by Bareau and uses autogenerated pressure in a single-stage reactor system to produce biomethane (Bareau, 2020). The pressure during the AHPD process causes most of the carbon dioxide to dissolve into the water phase, while most of the methane remains in the gas phase, which in principle allows for efficient and low-cost separation (Bareau, 2020). The gas output of AHPD consists of biomethane and surplus gas. The biomethane has a methane content between 90% and 95%, which makes the gas suitable to inject into the gas grid (Lindeboom et al., 2014). The surplus gas is produced when the pressure of the reactor drops. This gas is burned in a boiler to provide the heat input for the digestor. The digested sludge output of AHPD is dewatered using autogenerated pressure, which makes the centrifuge unnecessary. Furthermore, the end-use of the digested sludge can potentially be as a fertiliser instead of in a CHP, since the metal concentration may be lower than the maximum allowed metal concentrations in agriculture (Bareau, 2020). Because this claim could not be supported with measurements, both types of end-use are included in this research.

The GWP of the scenarios is calculated using a consequential Life Cycle Assessment (cLCA). This type of LCA is suitable since changes are made to the technologies within the system. The system boundaries of this cLCA are from gate to grave. The input at the gate is wastewater which needs treatment and the output at the grave is surface water quality. The functional unit for the comparison of the scenarios is: "Processing all population equivalents of the wastewater from the WWTP Amsterdam West until the water reaches surface water quality ". There are different definitions of PEs, but the one used in this research is based on 150 grams of Total Oxygen Demand (TOD) per person per day (Stowa, 2014-09). The wastewater treatment plant in Amsterdam West treats $906*10^3$ PE's per day (Waternet, 2015). The allocation method to compare the GWP of the different scenarios is substitution. This cLCA includes biogenic carbon dioxide, in contrast to current practices in LCA. This approach shows all emissions in wastewater treatment and indicates the remaining potential of CCU.

The results of this study are shown in Figure 1. The GWP for the entire WWTP Amsterdam West **including biogenic $CO_2$** is $51*10^3$ tonne $CO_2$-eq per year for the baseline scenario, $47*10^3$ tonne $CO_2$-eq per year for the A-trap scenario, between $32*10^3$ and $37*10^3$ tonne $CO_2$-eq per year for the AHPD scenario and between $32*10^3$ and $37*10^3$ tonne $CO_2$-eq per year for the $AH_2PD$ scenario. Compared to the baseline scenario, the GHG reduction potential is 8% for the A-trap scenario, between 27% and 37% for the AHPD scenario and between 28% and 37% for the $AH_2PD$ scenario. The GWP for the entire WWTP Amsterdam West **excluding biogenic $CO_2$** is $12*10^3$ tonne $CO_2$-eq per year for the baseline scenario, $8*10^3$ tonne $CO_2$-eq per year for the A-trap scenario, between $-5*10^3$ and $0*10^3$ tonne $CO_2$-eq per year for the AHPD scenario and between $-6*10^3$ and $-1*10^3$ tonne $CO_2$-eq per year for the $AH_2PD$ scenario. Compared to the baseline scenario, the GHG reduction potential is 35% for the A-trap scenario, between 102% and 143% for the AHPD scenario and between 109% and 150% for the $AH_2PD$ scenario. The variance in the GHG reduction of the AHPD and $AH_2PD$ scenario is caused by uncertainty in the end-use of the digested sludge, which can be as a fertiliser or in a CHP.

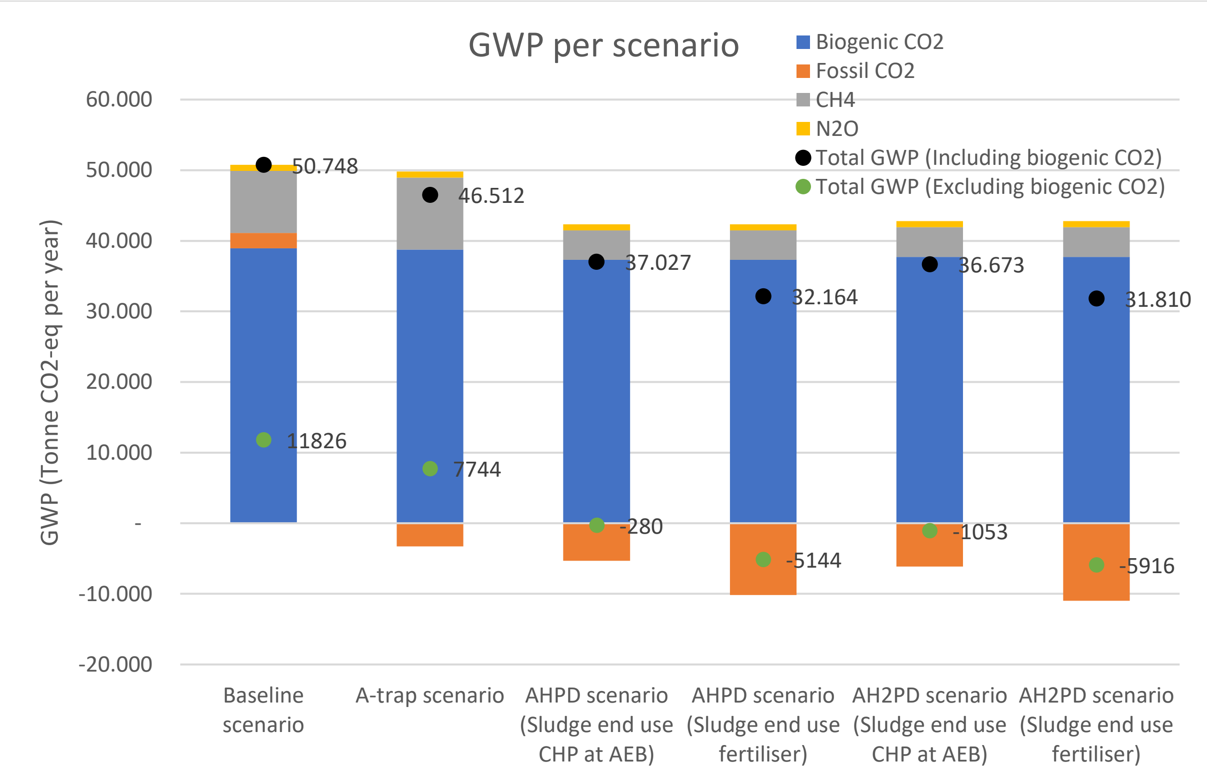


**FIGURE 1: SUMMARY GWP PER SCENARIO**

The robustness of the results is checked by performing a sensitivity analysis. This analysis showed that ranging one parameter at a time or changing one modelling assumption never makes the baseline or A-trap scenario outperform the AHPD and $AH_2PD$ scenarios. However, changing the allocation method to exergy makes the GWP of both AHPD scenarios lower than both $AH_2PD$ scenarios. This can be explained by the exergy losses in the conversion of hydrogen towards carbon dioxide.

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## List of abbreviations

| Abbreviation | Meaning |
|---|---|
| **AD** | Anaerobic Digestion |
| **AHPD** | Autogenerative High Pressure Digestion |
| **$AH_2PD$** | Autogenerative High Pressure Digestion<br>Including the injection of $H_2$ |
| **$AH_3PD$** | Autogenerative High Pressure Digestion<br>Including the injection of $H_2$ and $CO_2$ |
| **$AH_{(x)}PD$** | Used if the AHPD technology is mentioned<br>(with or without the injection of $H_2$ and/or $CO_2$) |
| **aLCA** | attributional Life Cycle Assessment |
| **AT** | Aeration Tank |
| **Biogas** | Biological produced natural gas<br>$CH_4$ % < 90% |
| **Biomethane** | Biological produced methane<br>$CH_4$ % > 90% |
| **BOD** | Biological Oxygen Demand |
| **CCS** | Carbon Capture and Storage |
| **CCU** | Carbon Capture and Utilisation |
| **CHP** | Combined Heat and Power |
| **cLCA** | consequential Life Cycle Assessment |
| **COD** | Chemical Oxygen Demand |
| **ds** | Dry Substance |

| | |
|---|---|
| | indicates the weight without water |
| **GHG** | Greenhouse Gas |
| **GWP** | Global Warming Potential |
| **IDS** | Inorganic dry substance |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LCA** | Life Cycle Assessment |
| **LCIA** | Life Cycle Impact Assessment |
| **NG** | Natural Gas |
| **$Nm^3$** | Normal cubic meter<br>1000 litres of gas at a temperature of 0 °C (273.15 °K) and a pressure of 1,01325 bar |
| **ODS** | Organic Dry Substance |
| **PE** | Population Equivalent |
| **PEC** | Primary Energy Content |
| **PP** | Power Plant |
| **PST** | Pre-Settling Tank |
| **ST** | Settling tank |
| **Surplus gas** | Secondary gas stream of $AH_{(x)}PD$. Similar composition as biogas. |
| **TOD** | Total Oxygen Demand |
| **WWTP** | Wastewater Treatment Plant |

# 1. Introduction

Global anthropogenic Greenhouse Gas (GHG) emissions have increased by 70% from 1970 towards 2004 and are expected to increase even further, leading to an increasing global temperature (Metz et al., 2007). Many countries agreed in December 2015 that they want to undergo efforts to limit global warming, by signing the Paris Agreement (Rogelj et al., 2016). The key components of this agreement are national goals to reduce GHG emissions. The global energy production from fossil fuels is one of the major contributors to GHG emissions. These GHG emissions can be reduced by lowering the demand for energy, or by making the supply side more sustainable by switching fossil fuels towards renewables or low-carbon fossil fuels, and/or using carbon capture and storage (CCS) (Riahi et al., 2011). One promising renewable energy source is biomass. This fuel is in principle emission neutral if the used biomass is replaced by new biomass. This is because new biomass absorbs the same amount of carbon dioxide ($CO_2$) using photosynthesis as the emitted $CO_2$ of the used biomass. The emissions of using biomass could even be negative when used in combination with CCS.

One sustainable source of biomass for energy production is the sludge coming from Wastewater Treatment Plants (WWTP's). Sludge is the waste product from WWTP's and mainly consist of organic material, nitrogen and phosphor. WWTP's emit biogenic GHG emissions during the oxidation process of the sludge and the usage of biogas in a CHP or torch. Also, fossil emissions are emitted due to the external electricity and heat demand of the installations and the transportation of sludge. All WWTP's in the Netherlands used 721 GWh of electricity in 2008, which was 0.6% of the total Dutch electricity demand (van Voorthuizen et al., 2009). The emissions coming from the biological processes are not quantified so far. However, based on a quick calculation using the Chemical Oxygen Demand (COD) of the sludge, these biogenic emissions are estimated to be in the order of 40 kg $CO_2$-eq per person per year. The energy usage and emissions of WWTP's can potentially be reduced by removing more sludge from the wastewater (K. Zagt, personal communication, June 7, 2019). This would have direct climate benefits since the additional sludge would have otherwise been oxidised towards $CO_2$. The sludge can be digested to produce biological produced natural gas (biogas). Biogas can be seen a carbon-neutral fuel since the $CO_2$ emissions from burning it belongs to the short carbon cycle. Therefore, the Global Warming Potential (GWP) of energy from biogas is smaller than that of fossil fuel-based Natural Gas (NG) (Cherubini et al., 2011).

Injecting biogas into the gas grid can replace fossil fuel-based natural gas and can, therefore, reduce the fossil GHG emissions of using the gas from the grid. Furthermore, the reduction of fossil fuel-based natural gas reduces the risk of small magnitude earthquakes in Groningen (van Eck et al., 2006). One serious problem of biogas is that the energy content, indicated by the Wobbe-index, is not high enough to inject it into the natural gas grid. For Dutch natural gas, the Wobbe-index should be between 43.5 and 44.4 MJ per Normal Cubic Meter ($Nm^3$) (Zachariah-Wolff et al., 2007). This range is important because it makes sure that appliances running on natural gas have complete combustion, do not overheat and have a steady flame. Most biogas in WWTP is produced by Anaerobic Digestion (AD) and has a carbon dioxide ($CO_2$) content between 30 and 40% (Lindeboom et al., 2012). The high $CO_2$ content lowers the Wobbe-index, which is one of the reasons that the gas cannot be directly injected into the gas grid. Upgrading biogas from AD to a higher Wobbe-index is possible by separating the CO2 from the methane. However, it is costly since additional pumps, compressors, membranes, gas treating equipment, and external energy is needed (Lindeboom et al., 2012). Because of the expenses of upgrading biogas, most biogas is directly consumed in a Combined Heat and Power (CHP) plant, which produces renewable electricity and heat. A part of this electricity and heat production is directly used in the WWTP and the AD.

Bareau developed a new digestion method, which uses autogenerated pressure in a single-stage reactor system to produce biogas with a higher methane ($CH_4$) content (Bareau, 2020). This approach is called Autogenerative High-Pressure Digestion (AHPD). The pressure during the AHPD process causes most of the $CO_2$ to dissolve into the water phase, while the produced $CH_4$ remains in the gas phase, which in principle allows for an efficient and low-cost separation (Bareau, 2020). As a result, the Wobbe-index of the biomethane is high enough to directly inject the gas into the gas grid, meaning there is no requirement for upgrading the gas. This is already demonstrated in the pilot plant of Bareau, where measurements of the $CH_4$, concentration ranged from 78.3 to 92.2 mol % (Bareau, 2020) The rest of the gas is mainly $CO_2$, but also $N_2$ and $O_2$ in small concentrations. An additional advantage of the autogenerated pressure is that no additional compressors are needed to inject the biomethane into the gas grid. It is expected that the AHPD technology can produce more biomethane if the Pre-Settling Tank (PST) of wastewater treatment is replaced by an A-trap which recovers more organic material from the wastewater (K. Zagt, personal communication, June 7, 2019). An A-trap is the first part of the German AB-system, which stands for Adsorption Belehbung Verfahren (Stowa, 1998-29). Last but not least, the potential addition of Hydrogen ($H_2$) or $H_2$ and Carbon Dioxide ($CO_2$), may increase biomethane yields. The addition of $H_2$ is referred to as the $AH_2PD$ process. If $CO_2$ and $H_2$ are added the process is called $AH_3PD$.

Even though wastewater treatment and sludge processing are highly connected processes, they are often treated separately in literature. For example, Dumaij & Wilschut (2012) only took wastewater treatment into account, while Boersma (2014) only researched sludge processing methods. This research will use an integral approach, meaning both the GHG emissions of the waterline and the emissions of the sludge line are assessed. This will only be possible with detailed information about the in- and outputs of the different processes within WWTP and sludge processing. Unfortunately, this detailed information is not modelled so far by waterboards (P. Vriend, personal communication, October 9, 2019; S. Mol, personal communication, October 30, 2019; S. Koning, Personal communication, November 1, 2019). Therefore, this research adds to existing literature by modelling the mass and energy flows of the entire process, from the incoming wastewater until the outgoing purified water. Furthermore, the significant improvements and associated GHG benefits of installing an A-trap in combination with the $AH_{(x)}PD$ technology have not been assessed and quantified in detail so far. This research will quantify the GHG reduction potential of this new technology. This is done by performing a consequential Life Cycle Assessment (cLCA) on the greenhouse gas emissions of the current scenario and comparing them with the scenarios containing an A-trap, an A-trap and AHPD and an A-trap with $AH_2PD$. Most LCA's do not assess biogenic $CO_2$ emissions since they belong to the short carbon cycle (Baumann & Tillman, 2004). This research adds to existing literature by including and quantifying these emissions since they contribute equally to global warming and reducing these emissions using Carbon Capture and Utilization (CCU) with the $AH_{(x)}PD$ technologies could replace the use of fossil fuel-based natural gas.

The system boundaries of the cLCA in this research are from gate to grave. This perspective covers the incoming wastewater towards the outgoing purified water. The research- and sub-questions, which can be found underneath, will be answered based on input data from the WWTP Amsterdam West.

**"How can the mass and energy flows of wastewater treatment be modelled and how can the change in mass and energy flows, caused by new technologies, be incorporated into this model?"**

**"What is the greenhouse gas emission reduction potential of the autogenerative high-pressure digestion technology compared to the baseline scenario* from a gate to grave perspective?"**

1. What are the greenhouse gas emissions to treat the wastewater of all population equivalents (PE's)** of Amsterdam west in the baseline scenario*?

2. How do these emissions change if the PST is replaced by an A-trap?
3. How do these emissions change if the PST is replaced by an A-trap and the AD process is replaced by AHPD?
4. How do these emissions change if the PST is replaced by an A-trap and the AD process is replaced by $AH_2PD$?

* The baseline scenario consists of a pumping station, bar screen, grease removal, pre-settling tank, aeration tank and settling tank for the wastewater treatment. The sludge line consists of an AD, a centrifuge and a CHP plant to burn the digested sludge. The low calorific biogas (60% methane) produced with AD, is burned for 87% in a CHP and 13% in a torch (Waternet, 2015).

** One PE describes an amount of oxygen needed to treat the incoming wastewater of one person to a WWTP. Traditionally one PE equals 54 grams of Biological Oxygen Demand (BOD) per person per day (Stora, 1985-4). However, the PE's reported by WWTP's are based on 150 grams of Total Oxygen Demand (TOD) per person per day (Stowa, 2014-09). This research uses the PE definition of 150 grams of TOD per person per day.

The first research question is needed to understand the process at a WWTP. The results of this question will be an input for the second research question and the corresponding sub-questions. Answering the second research questions will give insights into the current GHG emissions, and the GHG reduction potential of an A-trap with or without AHPD and $AH_2PD$, of the WWTP Amsterdam West. Because the majority of the WWTP's in the Netherlands are operated in the same way as the WWTP in Amsterdam West, the results of this research can be used for other WWTP in the Netherlands as well. The results of this study should be revised when improvements are made to the baseline scenario since this could influence the results. One should be aware that the heat usage of the digesters is climate-specific, and that wastewater composition can differ per area since it depends on the number of households, industry, the type of sewage and the weather. Because of this, it is not recommended to directly use the results of this study in other countries. Because of the scale and timeframe of this research, there is chosen to only focus on one impact category; the GWP. This impact category is chosen because of the large amount of GHG emissions in WWTP's.

The introduction is followed by the theory section. This section covers the basics of the LCA methodology. Hereafter, the fundamentals principles of WWTP's, AD, AHPD, and $AH_2PD$ are explained in the system description. This is followed by the method section which covers the case study, the goal and scope of the LCA, the system boundaries, the allocation of the end products, the data collection, and the sensitivity analysis. This section is followed by the inventory analysis where all mass and energy flows within the system boundaries are calculated and quantified. Next, the GWP of all different scenario is displayed and explained in the result section. After the results, the sensitivity analysis is performed which deals with the robustness of the results. This is followed by the discussion and the conclusion.

Bareau is the commissioner of this study. They proposed the idea of installing an A-trap in combination with AHPD or $AH_2PD$. Furthermore, they developed the $AH_{(x)}PD$ technology and they have a small AHPD reactor that provides information based on measurements about their technology. Despite Bareau is involved, this study is conducted independently and according to scientific standards. Furthermore, data provided by Bareau will be checked using literature or expert opinions were possible.

# 2. Theory

This chapter focusses on important concepts underlying this research. First the theory about mass balancing is discussed in section 2.1. Hereafter the framework of LCA is explained in section 2.2.

## 2.1 Mass balancing

A mass balance relies on the principle that mass cannot disappear or be created spontaneously (Jurendic, 2014). According to this principle, the input to a system should equal the output + accumulation in the same system. If a chemical reaction takes place, there can be a change in the composition of the reactance, but there cannot be a change in mass in the system. Making a mass balance consists of a few steps. First, information about all mass inputs in the inlet and exit streams needs to be collected. The next step is to select a functional unit. This unit can, for example, be based on an amount of mass entering the system per time. The third step is to use the principle of mass balancing (input = output + accumulation) to solve each unknown in the mass balance. Lastly, it is recommended to visualise all mass flows in the flow chart.

For mass balancing in WWTP's, all in- and outgoing sludge flows should be measured (Puig et al., 2008). This can be done by modelling the Chemical Oxygen Demand (COD) or Organic Dry Substance (ODS) in the sludge through the entire system.

## 2.2 Life cycle assessment

The goal of a LCA is to assess the climate impact of a product, process or human activity over its life cycle (Curran, 2013). What is covered with the life cycle depends on the scope of the LCA. The complete lifecycle (cradle-to-grave) consists of the extraction of the raw materials, the production and distribution, the use, and the reuse, recycling or waste management (Morbidoni et al., 2012). It is also possible to conduct a partial LCA, which can be from cradle-to-gate (extraction and production), gate-to-gate (one process in the production chain), or gate-to-grave (incoming products towards recycling or waste management). Every LCA should consist of four stages, which are displayed in Figure 2 (ISO, 2006). These stages are the goal and scope definition, inventory analysis, impact assessment, and interpretation. The four stages are explained below.

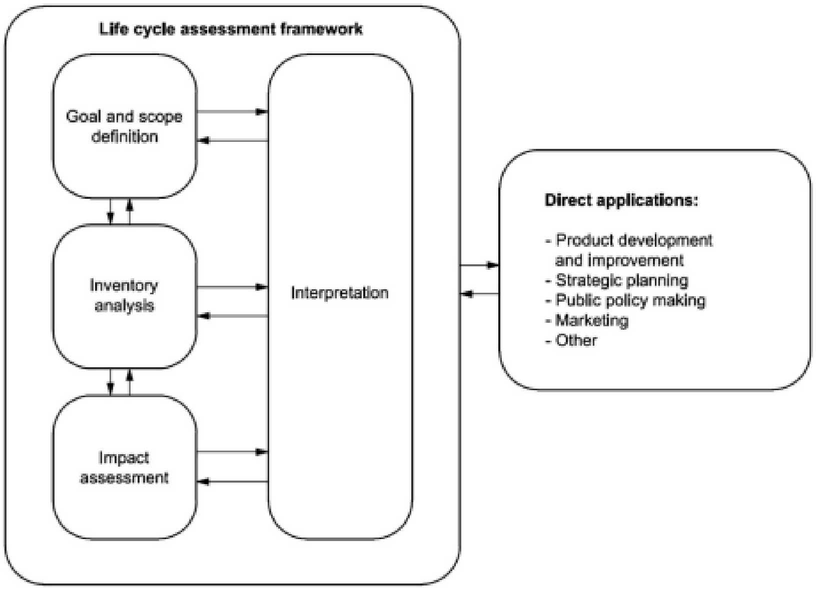


**FIGURE 2: THE LCA FRAMEWORK (ISO, 2006)**

### 2.2.1 Goal and scope definition

The goal and scope definition include the intended application of the study, the reason for carrying out the study and it should be specified for who the results of the study are (Baumann & Tillman, 2004). Normally the goal and scope definition of an LCA describes the product or function in terms of a functional unit and the system boundaries (Rebitzer, 2004). The functional unit helps to compare the emissions of different processes or services with each other. The functional unit should focus on the product function, rather than production or consumption volumes (Baumann & Tillman, 2004). The system boundaries describe what is and is not included in the LCA. The system boundaries can be specified in different dimensions, which are: 1: Boundaries concerning natural systems. 2: Geographical boundaries, 3: Time boundaries and 4: Boundaries within the technical systems (Baumann & Tillman, 2004). In the case different products or functions are products of one process, it can be hard to set the system boundaries. This is because the impact of the process is expressed in one single product or function (Baumann & Tillman, 2004). This is called the allocation problem. Allocation can be performed by partitioning or by system expansion. Allocation by partitioning divides the emissions and resource consumption of the multiple processes and the process up-stream (Baumann & Tillman, 2004). Allocation by system expansion credits the avoided up-stream emissions and resource consumption to the multiple processes. The allocation standards according to ISO (2006) are shown below in the order they purpose.

1. Avoid allocation by increasing the detail in the model or system expansion
2. If it is not possible to avoid the allocation, use partitioning between the different processes. This partitioning should reflect a physical relationship.
3. If it is not possible to use partitioning using a physical relationship, use another relationship. For example, a monetary one.

In contrast to the ISO (2006) standards, most authors use system expansion for consequential LCA's (cLCA's) and partitioning for attributional LCA's (aLCA's) (Baumann & Tillman, 2004; Ekvall & Weidema, 2004). A cLCA describes new additions or changes to the system. A cLCA covers the full upstream and downstream production by expanding the system (Weidema et al., 2018). Covering more activities lowers the precision of a cLCA, but the completeness improves since interlinked activities are also accounted for. In case an existing scenario is described, it is better to use an aLCA. An aLCA does only look at product outputs (Weidema et al., 2018). This makes this type of LCA less complete, but generally more precise.

### 2.2.2 Inventory analysis

The inventory analysis includes a flowchart, the data collection and the calculation of environmental loads of the system (Baumann & Tillman, 2004). The flowchart consists of all modelled flows of the system between the different processes and should be in line with the system boundaries. The data collection includes data about the process itself; energy usage, raw materials, ancillary inputs and emissions to air, land, and water. Also, data about other processes may be collected, in case allocation is required. The calculation stage includes the normalisation of data, the calculations of flows within the system boundaries and calculating the flows passing the system boundaries. At the end of the calculation stage, all resource use and emissions are summed up and all calculations are documented.

### 2.2.3 Impact assessment

The aim of the Life Cycle Impact Assessment (LCIA) is to convert the environmental loads found in the inventory analysis into environmental consequences (Baumann & Tillman, 2004). Some examples of these consequences could be acidification, loss in biodiversity and ozone depletion. Converting environmental loads into environmental consequences reduces the number of parameters, which helps in the communication of the results. The impact assessment consists of three mandatory stages, and four optional stages, which are listed and explained below according to Baumann and Tillman (2004).

1. **Impact category definition**: The relevant impact categories are selected in this stage. These impact categories should be in line with the goal and scope of the LCA. The impact categories can relate to resources, human health, economic consequences and/or untraceable in- and out-flows.
2. **Classification:** This stage sorts the results and aligns them to the impact categories (stage 1)
3. **Characterisation:** All environmental impacts are weighted to assign an equivalent indicator. E.g. the GWP can be measured by $CO_2$-eq emissions.
4. **Normalisation (optional):** Here the impact of the results is related to for example the total emissions of a country. This helps to understand the magnitude of the impact.
5. **Grouping (optional):** In case there is more than one characterisation result, it is possible to group them. This can be done based on their impact priority (low, medium or high) or their impact area (local, regional or global)
6. **Weighting (optional):** If there are multiple impact categories in the LCA, they can be weighted. This gives insight into the relative environmental impact of one impact category against another.
7. **Data quality analysis (optional):** This stage consists of different techniques that help to better understand the outcomes of the LCIA. Examples of data quality analysis are a sensitivity analysis, dominance analysis or uncertainty analysis.

### 2.2.4 Interpretation

The last stage of the LCA is the interpretation of the results. In this stage, the results are assessed to conclude. The visualisation of the results in tables, bar- and flow-charts can be helpful to assess the results. Furthermore, the optional data quality analysis of the LCIA can give insights into the robustness of the results.

# 3. System description

The system description consists of the basics principles of wastewater treatment and sludge processing. This is followed by the case study description. This section describes the case study and deals with the implications of the calculation method for the case study.

## 3.1 Wastewater treatment

The Netherlands counts 352 WWTP's, which are owned and controlled by 21 different waterboards (Watersector.nl, 2019). Figure 3 shows the scale of one of the bigger wastewater treatment plants located in Amsterdam West. The round and closed tanks without the stares on top are the Pre-Settling Tanks (PST's). The round and closed tanks with the stares on top are Aeration Tanks (AT's). The covered round tanks are (secondary) settling tanks (ST's). The three Anaerobic Digesters (AD's) can be found in the right lower part of the picture. All WWTP's in the Netherlands process approximately $1.9 * 10^9$ $m^3$ of wastewater per year (CBS, 2018). The costs of the treatment of all the waterboards in the Netherlands are in the order of €$1.0*10^9$ per year (VEMW, 2019)

**FIGURE 3: OVERVIEW OF THE WWTP AMSTERDAM WEST (WATERNET, 2019)**

Not all WWTP's work the same, therefore a more general overview of the treatment steps of a WWTP is given in this section. Different processes occur in a WWTP, which can be divided into primary-, secondary- and post-treatment. Post treatment is not covered in this research, since this process does not occur in the majority of the WWTP's. The primary and secondary treatment processes are explained underneath. After the wastewater treatment, the sludge needs to be processed as well. This is covered in section 3.2.

### 3.1.1 Primary treatment

The WWTP starts with the primary treatment. The aim of the primary treatment is to filter out large objects and to remove sludge from the wastewater. This stage consists, most of the time, of a pump station, a bar screen, a grease and grit removal tank and a primary settling tank. The pump station uses electricity to pump the wastewater from the sewer system through the entire wastewater treatment plant. First, the wastewater goes through a bar screen. The aim of the bar screen is to remove large objects, to prevent damage or a clog in other treatment steps. After the bar screen, it is possible to place an even finer screen, which can be a contagious belt screen, drum screen or a step screen. The aim of this finer screen is to remove even more solids. After the screens, the wastewater goes to the grease and grit removal. The water flow rate is lowered in this removal stage to let grit settle on the floor of the tank. The outlet of the grit and grease removal tank is lower than the water level. Because grease floats, it can be removed from the top of the tank. The last phase of the primary treatment is the Pre-Settling Tank (PST). The function of this tank is to remove a part of the organic materials upfront, to lower the energy consumption of the biological treatment. The PST removes between 25 and 40% of the Chemical Oxygen Demand (COD) (Metcalf & Eddy, 2003). This is done by collecting the floating material in the tank with a surface scraper and removing the organic materials from the bottom with a bottom scraper.

It is possible to replace the PST (physical process) with an A-trap (biological process). Other differences are that the sludge retention time is longer in an A-trap than in a PST and that an A-trap is aerated in contrast to a PST (KWR, 2014). It is advised to place an A-trap in combination with AHPD because more organics are be subtracted from the wastewater. Furthermore, an A-trap allows having a more efficient nitrogen removal (KWR, 2014), which is explained in section 3.2. After the PST or the A-trap, the remaining wastewater goes to the next phase, which is the secondary treatment.

### 3.1.2 Secondary treatment

The aim of the secondary treatment is to remove the remaining biological content and the nitrogen compounds, like ammonium ($NH_4$), of the wastewater. Depending on the type of bacteria in the tank, nitrogen can be removed using the nitrification/denitrification process or the anammox process. After the removal of organics, phosphate, and ammonium, the wastewater enters a settling tank. In most WWTP's, nitrogen and the organic fraction of sludge are removed using an aeration tank, consisting of an anoxic and an aerated zone. Because multiple processes occur in the aeration tank, an overview in more detail is given in Figure 4.

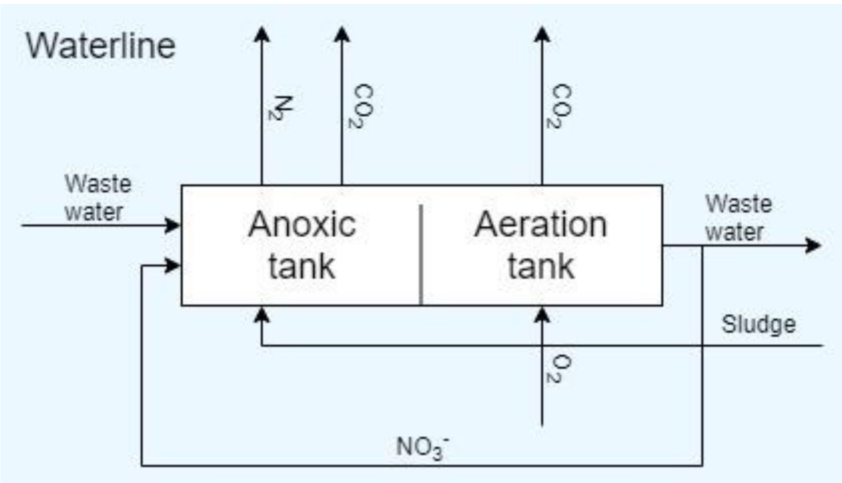


**FIGURE 4: PROCESSES OCCURRING IN THE AERATION TANK**

The explanation of the AT starts with the aerated zone because the nitrate formed in the aerated zone is recirculated to the anoxic tank where it is needed for denitrification. The oxidation tank removes the organic fraction (Organic Dry Substance (ODS)) and nitrogen compounds from the wastewater. The ODS is converted into using heterotrophic bacteria in the aeration tank. The injected oxygen is used by these bacteria to grow. An example of the reaction equation of the oxidation of ODS can be found in equation 1. Sewage sludge consists of fats (0% to 40%), carbohydrates (25% to 30%), lignin (10% to 40%) and proteins (25% to 30%) (Bareau, 2020). The process is illustrated by the conversion of glucose, which is shown in Formula 1. This shows that the removal of one mole of glucose uses 6 moles of $O_2$ and produces 6 moles of $CO_2$ and 6 moles of $H_2O$.

**[1]**: Oxidation of ODS = $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$

**Nitrification/denitrification:** The other process occurring in this tank is the conversion of ammonium into nitrate. This is done in a conventional WWTP using the nitrification/denitrification process. The reaction equation for this process is shown in Formula 2.

**[2]**: Nitrification/denitrification aeration tank = $2\ NH_4^+\ 3\ O_2 \rightarrow 2\ NO_2^- + 4H^+ + 2\ H_20$

$2\ NO_2^- + O_2 \rightarrow 2\ NO_3^-$

The nitrate is recycled internally to the anoxic tank. In the absence of oxygen, the nitrate reacts with the organic compounds from the injected activated sludge into elementary nitrogen. An example of this reaction equation (with ODS represented by glucose) can be found in Formula 3. From reaction equation 2 and 3 can be concluded that for every mole of removed ammonia, 2 moles of $O_2$ are needed, and 0.25 mole glucose is needed. This produces 2 $H^+$ ions, 2.5 moles of $H_2O$, 1.5 moles of $CO_2$ and 0.5 moles of $N_2$

**[3]:** Nitrification/denitrification anoxic tank = $4\ NO_3^- + C_6H_{12}O_6 \rightarrow 6\ CO_2 + 6\ H_2O + 2\ N_2$

**Anammox process:** In scenarios where additional sludge is recovered from the wastewater (for example using an A-trap), the nitrification/denitrification process shifts towards the anammox process. The anammox process happens in the same tank as the nitrification/denitrification process. The process can be seen in Figure 5. There are a few differences compared to nitrification/denitrification. The first is that autotrophic bacteria instead of heterotrophic bacteria are used. As a result, this process uses less than half of the oxygen demand as the nitrification-denitrification process. Furthermore, no ODS is needed for the reduction of ammonium. The removal of the ODS in the aeration tank remains the same. Lastly, the anammox process is temperature-sensitive, meaning the process works less efficiently at lower temperatures. The reaction equation for the anammox process is shown in equation 4. The anammox process requires closely regulated oxygen supply in the aeration tank, since an excess of oxygen results in the unwanted conversion of $NO_2^-$ into $NO_3^-$. The anammox bacteria operate in the anoxic tank where $NO_2^-$ and $NH_4^+$ is converted into $N_2$. From reaction equation 4 can be concluded that for every mol of $NH_4^+$ removed, 0,75 moles of $O_2$ are needed. This produces 1 $H^+$ ion, 1.5 moles of $H_2O$ and 0.5 moles of $N_2$

**[4]:** Anammox process = $2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O$

$NO_2^- + NH_4^+ \rightarrow N_2 + 2\ H_2O$

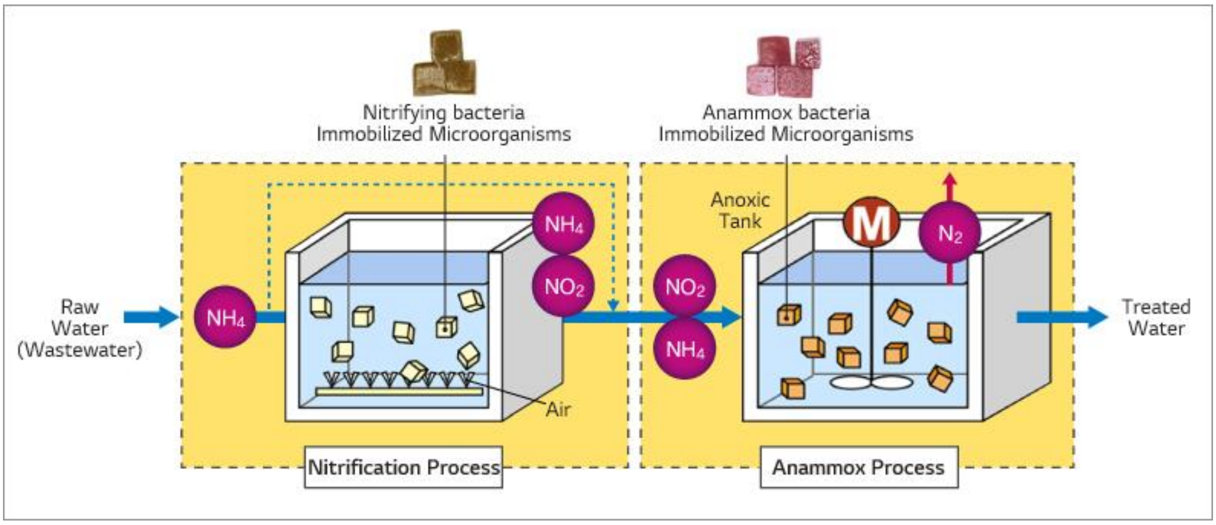


**FIGURE 5: THE ANAMMOX PROCESS (LG-HITACHI WATER SOLUTIONS, 2014)**

Supplying oxygen for the removal of nitrogen and sludge is an energy-intensive process. This process uses in the Netherlands on average 133 MJ $_{prim}$ / (PE $_{removed}$ * year) (Unie van Waterschappen, 2014). This is between 55% and 75% of the total energy consumption of a WWTP (Stowa, 2018-69). Because the anammox process uses less than half of the oxygen for nitrogen removal, it uses less energy for the nitrification/denitrification process. However, the emissions of removing organic materials remains the same. The energy demand in combination with the biogenic $CO_2$ emissions from ODS removal contributes to the high climate impact of this treatment stage.

After the aeration tank, the wastewater goes to the Settling Tank (ST). This tank removes the activated sludge from the wastewater. A part of this sludge is brought back into the beginning of the aeration tank because it contains a lot of microorganisms that speed up the breakdown of organic matter. The other part of the sludge is going directly to the sludge treatment. After the secondary treatment, it is optional to treat the wastewater further in the post-treatment. The mass and energy flows for the primary and secondary wastewater treatment are visualised in Figure 6.

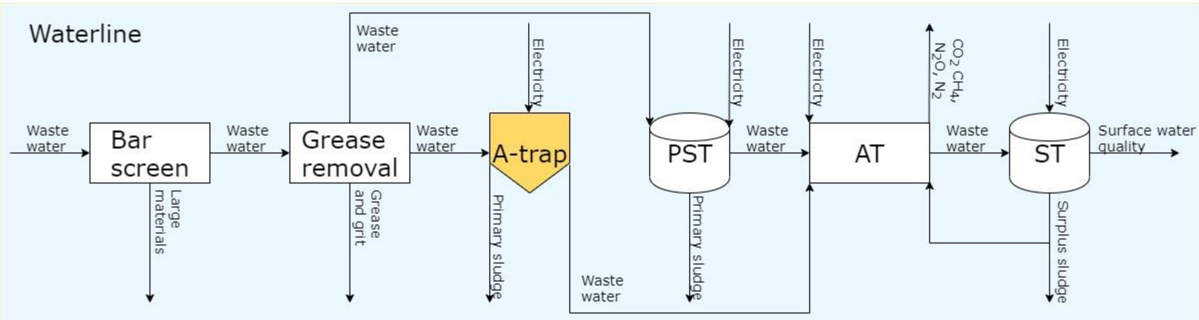


**FIGURE 6: MASS AND ENERGY FLOWS FOR THE WATERLINE**

### 3.1.3 $N_2O$ emissions

Under ideal circumstances, all ammonium is converted into nitrate, which was shown in equations 2, 3 and 4. However, nitrogen can be present in different forms under real circumstances. Figure 7 shows all biological nitrogen conversion possibilities of WWTP's (Kampschreur et al., 2009). As can be seen from this figure, one possible nitrogen form is Nitrous Oxide ($N_2O$). Since the $GWP_{100}$ of $N_2O$ is 298 times that of $CO_2$ (Winnipeg, 2012), it is important to be aware of nitrogen in this form. These emissions can occur due to nitrification, denitrification and due to chemical reactions (Snip, 2010). Multiple studies have been performed on the $N_2O$ emissions of WWTP, where measurements of concentrations ranged between 0.035% and 95% $N_2O$ emissions of the total nitrogen load (Kampschreur et al., 2009). However, most measurements show $N_2O$ concentrations below 1%. Currently, Dutch WWTP's are allowed by the Intergovernmental Panel on Climate Change (IPCC) to report their $N_2O$ emissions based on one study performed with measurements of 1993 for a small WWTP in Durham (Kampschreur et al., 2009). According to this study, the $N_2O$ emissions of WWTP using nitrification/denitrification are 3.2 g of $N_20$ per person per year (Czepiel et al., 1995). This corresponds with 0.035% of the incoming nitrogen load.

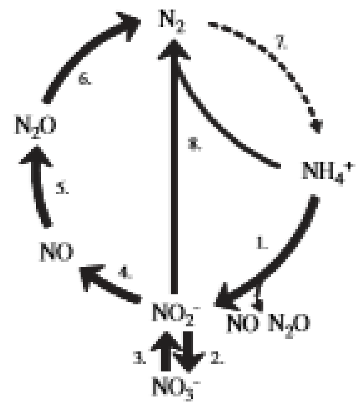


**FIGURE 7: BIOLOGICAL NITROGEN CONVERSIONS (KAMPSCHREUR ET AL., 2009)**

For the anammox process, the $N_2O$ emissions may be different. Low oxygen concentrations and high nitrite concentrations potentially increase $N_2O$ emissions (Stowa, 2008-18). The anammox process has higher concentrations of nitrite in the nitrification reactor, increasing the possibility of $N_2O$ emissions. However, because of conversion of nitrite is more direct, the possibility of $N_2O$ emissions decreases. Furthermore, the oxygen concentrations are lower during the anammox process, increasing the possibility of $N_2O$ emissions. Because the effect of the anammox process on nitrogen emissions is not clear, no difference in $N_2O$ emissions is assumed in this research. The emissions factor used for both processes can be found underneath.

**3.2 g $N_2O$ per person per year** = 0.035% of the incoming nitrogen load. Because of the high uncertainty, the sensitivity analysis ranges the $N_2O$ emissions of both processes from 0.035% towards 1% of the incoming nitrogen load.

## 3.2 Sludge treatment

There are multiple options to process sludge from a WWTP. Three possibilities are explained in this section. The first is to partly dry the sludge, transport it by truck and burn it in a CHP. The other two options are to digest the sludge using AD or $AH_{(x)}PD$ and dry the remaining sludge before it is transported and burned in a power plant, or in case of $AH_{(x)}PD$ possibly used as a fertiliser. Figure 8 shows the different sludge treatment options, which are from left to right: The CHP at AEB, an AD and the $AH_{(x)}PD$ computer model of the installation in Ameland.

FIGURE 8: SLUDGE TREATMENT: CHP (LEKHABO, N.D), AD (MSU, 2013), AH$_{(x)}$PD (BAREAU, 2020)

### 3.2.1 Burning sludge in a CHP

About half of the sludge in the Netherlands is processed in the way as illustrated in Figure 9 (K. Zagt, personal communication, August 8, 2019). The orange highlight means that a process or flow is optional. Before the sludge is burned in a power plant, the water content is reduced. The dewatering stage (using a centrifuge) reduces the water content from approximately 4.5% Dry Substance (DS) towards approximately 24% DS. This process generally injects low amounts of FeCl3 to prevent phosphor and sulphur entering the wastewater. Furthermore, a low amounts of Poly Electrolyte (PE) are often injected because it helps with the dewatering process. The wastewater which is separated in the centrifuge needs treatment and is therefore often brought back to the WWTP. After the centrifuge, it is optional to dry the sludge even further to a minimum of 40% DS. The drying stage evaporates the water from the sludge, therefore, the water coming from this stage is of surface water quality. The drying stage can dry the sludge even further until values of 90% DS. This depends on the transportation distance from the dryer to the power plant. E.g. a higher DS content means that the volume is less, and therefore, fewer trucks are needed to transport the sludge. Therefore, the DS content is generally higher for a WWTP which is located further away from the CHP. After the drying stage, the sludge goes towards a CHP. The CHP always produces heat but depending on the DS% of the sludge the CHP will produce electricity or use electricity and NG (IV-Groep, 2014). The power plant also produces contaminants in the flue gasses (Zn, Pb, Cu, and Hg), which should be treated before releasing it into the environment.

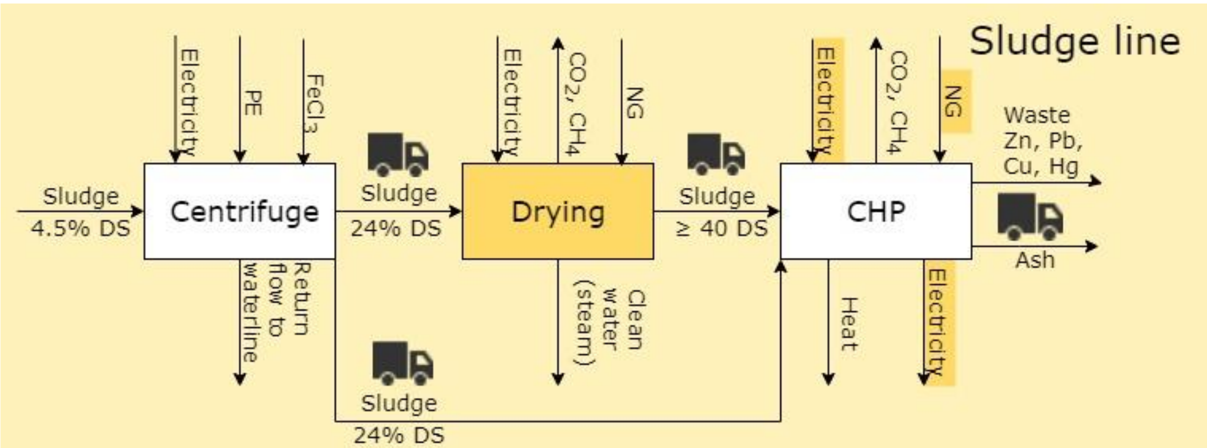


FIGURE 9: MASS AND ENERGY FLOWS FOR THE SLUDGE LINE

### 3.2.2 Digesting sludge using AD

Larger wastewater treatment generally digests their sludge using AD. About 50 percent of the sludge is treated this way (K. Zagt, personal communication, August 8, 2019). The AD technology produces biogas by the digestion of organic connections in the absence of oxygen, see the simplified reaction in Formula 5.

**[5]**: $C_6H_{12}O_6 \rightarrow 3\ CH_4\ (g) + 3\ CO_2\ (g)$

The biogas consists theoretically of 50% $CO_2$ and 50% $CH_4$ molecules. In practice, the methane concentration is between 55% and 70% and the $CO_2$ concentration is between 30% and 45% (Lindeboom et al., 2012). This is because the organics also consist of longer fatty acids chains than glucose. The biogas can be directly burned in a CHP or upgraded to inject it into the natural gas grid. Upgrading biogas is an expensive process since it required external energy inputs and/or investments for pumps, compressors, membranes, and gas treating equipment (Lindeboom et al., 2012). Therefore, this is only economically viable for biogas streams of more than 100 $m^3/h$ (Lindeboom et al., 2012). Because of this, less than 25% of the biogas is currently upgraded and 75% is directly burned in a CHP (CBS, 2018). After AD, the sludge still has approximately 65% of its ODS and is processed in the same way as in plants without AD, as shown in Figure 9. The mass and energy balance of the AD process is shown in Figure 10.

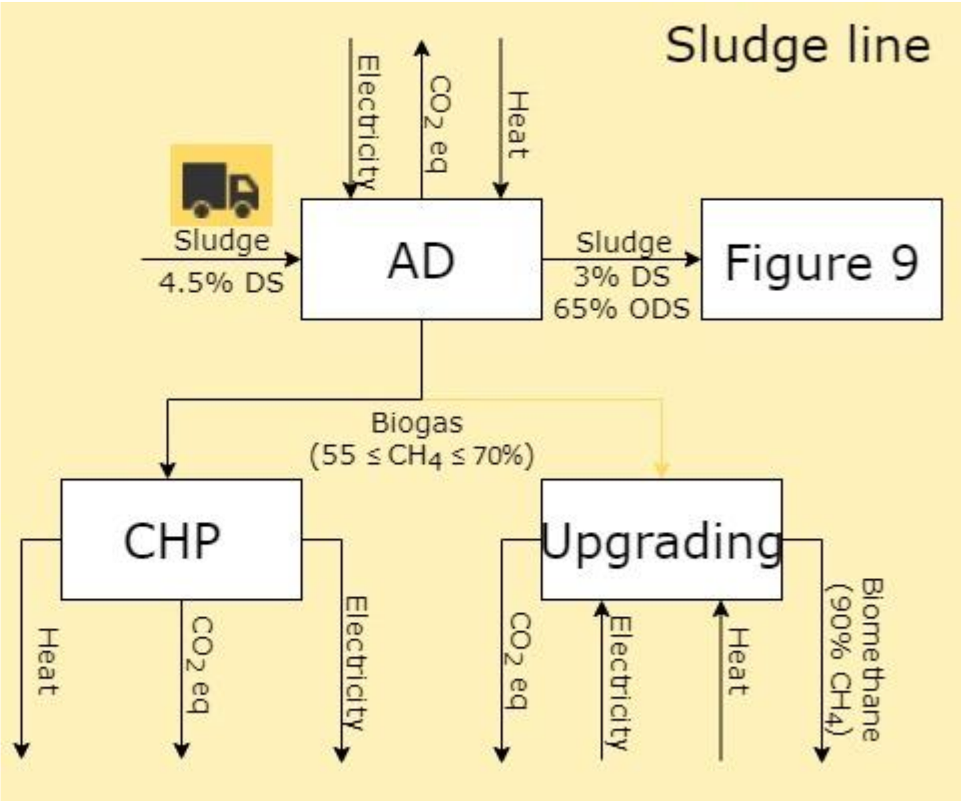


**FIGURE 10: MASS AND ENERGY FLOWS FOR SLUDGE LINE INCLUDING AD**

### 3.2.3 Digesting sludge using $AH_{(x)}PD$

Instead of using AD to make biogas it is also possible to process the sludge using the $AH_{(x)}PD$ technology, as illustrated in Figure 11. The simplified reaction equation of the AHPD process can be found in Formula 6. The ammonium is removed from the wastewater from using the anammox process. This process was already explained in section 3.1.2 (Formula 4)

**[6]:** $C_6H_{12}O_6\ (aq) \rightarrow 3\ CH_4 + 3\ CO_2$

Based on the reaction equation one should think that the biogas has the same concentration of $CH_4$ and $CO_2$ molecules as with the AD process. However, because AHPD occurs at a pressure of 20 bar, most of the $CO_2$ dissolves in the liquid, while most of the $CH_4$ remains a gas. Three processes take place at 20 bar, which results in a methane content of the biogas between 90% and 95% (Lindeboom et al., 2014). These processes are:

1. **Dissolving of gas**: The amount of gas that dissolves relates to the partial pressure and can be calculated using Henry's law (Rodriguez et al., 2016). This law can be defined as: Concentration of the gas in the liquid phase = Henry's constant * Partial pressure of the gas in the gas phase. The Henry constant of $CO_2$ is around 3 times higher than that of $CH_4$. This results in a $CH_4$ content in the gas of 82% and a $CO_2$ concentration of 18% at a pressure above approximately 3 bar (Rodriguez et al., 2016)
2. **Complexation:** Mostly dissolved $NH_3$ reacts under pressure with $CO_2$ to form $NH_2$-CO-$NH_2$ and $H_2O$ ($CO_2$ (g) + 2$NH_3$ (g) $\leftrightarrow$ $H_2N$-$COONH_4$ (s) $\leftrightarrow$ $NH_2$-CO-$NH_2$ (aq) + $H_2O$ (l)) (Rodriguez et al., 2016). This allows more $CO_2$ to dissolve in the liquid and therefore raises the $CH_4$ concentration of the gas.
3. **$CO_2$ equilibrium:** In water, $CO_2$ also reacts with water to form carbonic acid or even further to bicarbonate ($CO_2$ + $H_2O$ $\leftrightarrow$ $H_2CO_3$ $\leftrightarrow$ $H^+$ + $HCO_3^-$). This reaction also allows dissolving more $CO_2$ into the liquid. The $CO_2$ equilibrium and complexation increases the $CH_4$ concentration of the biomethane towards 90% to 95% (Lindeboom et al., 2012).

Another difference between $AH_{(x)}PD$ and AD is the energy needed for dewatering and drying. With $AH_{(x)}PD$ there is no additional energy needed for this process since the autogenerated pressure is used to dewater the sludge towards 20% DS (Bareau, 2020). Furthermore, the $AH_{(x)}PD$ process directly removes a part of the heavy metals (Zn, Pb, Cu, and Hg) from the sludge in the phosphor reactor (Bareau, 2020). This makes the heavy metal concentrations in the digested sludge per definition lower, which could make it possible to use the digested sludge from $AH_{(x)}PD$ in agriculture as a fertiliser. The maximum concentration of heavy metals in sewage sludge for usage in agriculture is shown in Table 1 (RVO, 2015). The concentration of heavy metals in the sludge of $AH_{(x)}PD$ was not measured before the end of this thesis. Because of this uncertainty, two different types of end-use of the digested sludge from $AH_{(x)}PD$ will be included in this research. The digested sludge can be used as a fertiliser if the concentration of heavy metals is lower or equal than the maximum concentration. Otherwise, the digested sludge should be burned in a CHP.

TABLE 1: MAXIMUM HEAVY METAL CONCENTRATION IN SLUDGE FOR USAGE IN AGRICULTURE

| Waste | Maximum concentration | Unit |
|---|---|---|
| **Zn** | 300 | mg / kg ds |
| **Pb** | 100 | mg / kg ds |
| **Cu** | 75 | mg / kg ds |
| **Hg** | 0.75 | mg / kg ds |

The AHPD process allows the addition of external $H_2$ or $H_2$ and $CO_2$. The addition of $H_2$ is called $AH_2PD$ and leads to the conversion of hydrogen and dissolved $CO_2$ into $CH_4$. This process is limited by the $CO_2$ production of the process described in equation 6. However, in practice, only 50% of the $CO_2$ reacts towards $CH_4$, since the methane concentration in the biomethane would otherwise exceed the wobbe index (Bareau, 2020). The pressure during $AH_2PD$ is reduced towards 8 bar since the higher pressure is not needed anymore to dissolve the $CO_2$ (Bareau, 2020). The $AH_2PD$ reaction equation is shown in Formula 7 and consists of two sub equations. According to Bareau (2020), this process has an efficiency of 90%. The rest of the $H_2$ produces heat.

**[7]:** $C_6H_{12}O_6 + 12\ H_2\ (g) \rightarrow 6\ CH_4\ (g) + 6\ H_2O\ (l)$

$C_6H_{12}O_6$ (aq) → 3 $CH_4$ (g) + ~~3 $CO_2$ (aq)~~

~~3 $CO_2$ (aq)~~ + 12 $H_2$ (g) → 3 $CH_4$ (g) + 6 $H_2O$ (l)

The addition of $H_2$ and $CO_2$ leads to the $AH_3PD$ process. Because external $CO_2$ is injected, the conversion of $H_2$ into $CH_4$ is not limited anymore by the $CO_2$ production of the digestion of sludge. The $AH_3PD$ reaction equation is shown in Formula 8 and consists of three sub equations. Forming one additional mole of $CH_4$ needs in theory 1 mole of injected $CO_2$ and four moles of injected $H_2$. This reaction used the bacteria of the sludge to convert $H_2$ and $CO_2$ into $CH_4$. Because this reaction does not depend on the conversion of sludge, this process is excluded from the research scope.

**[8]:** $C_6H_{12}O_6$ + 16 $H_2$ + $CO_2$ (g) → 7 $CH_4$ (g) + 8 $H_2O$ (l)

$C_6H_{12}O_6$ (aq) → 3 $CH_4$ (g) + ~~3 $CO_2$ (aq)~~

~~3 $CO_2$ (aq)~~ + 12 $H_2$ (g) → 3 $CH_4$ (g) + 6 $H_2O$ (l)

$CO_2$ (g) + 4 $H_2$ → $CH_4$ (g) + 2 $H_2O$ (l).

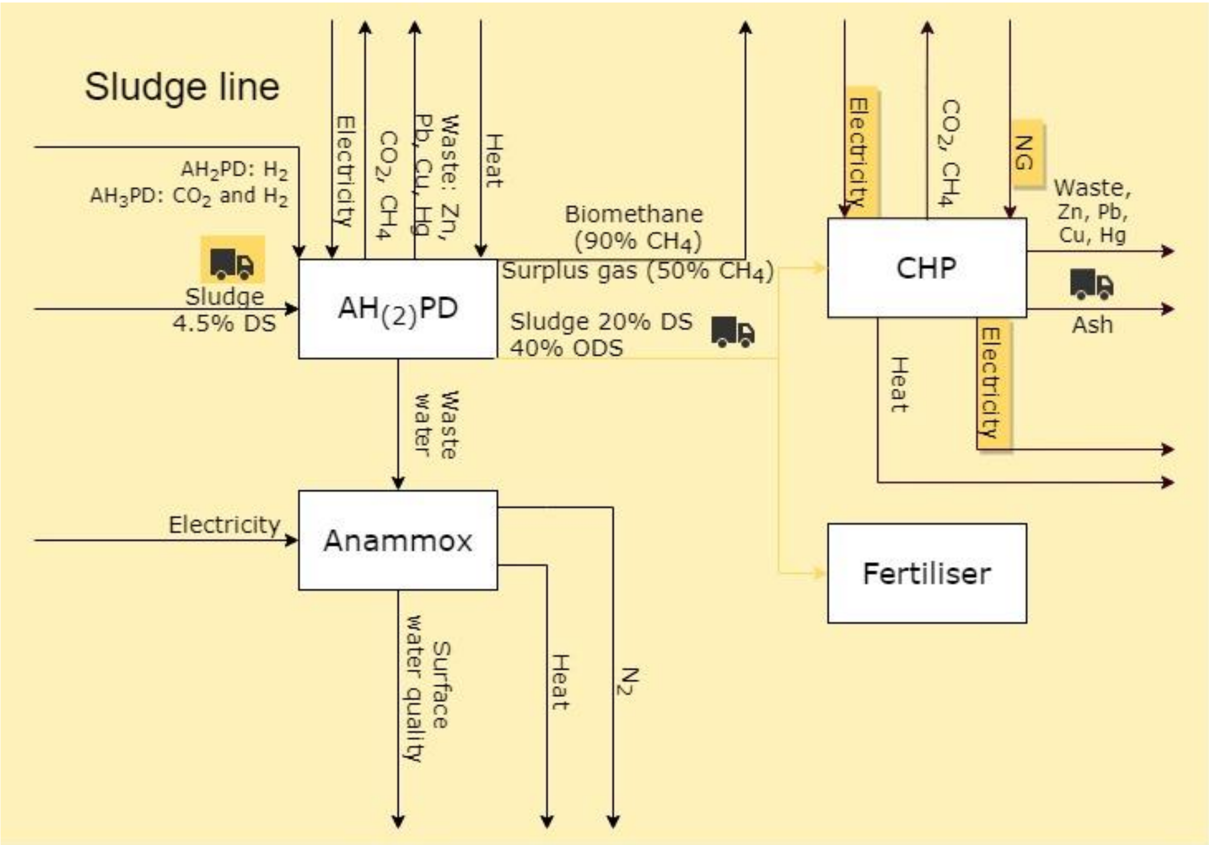


FIGURE 11: MASS AND ENERGY FLOWS FOR SLUDGE PROCESSING USING AHPD OR $AH_2PD$

## 3.3 Case study discription

Bareau, has a small scale $AH_{(x)}PD$ pilot plant located in Heerenveen. Furthermore, Bareau is going to build a full-scale operational $AH_{(x)}PD$ installation in Ameland. The case study in this research will be performed for the municipality of Gaasperdam. The municipality of Gaasperdam is currently exploring different possibilities to reduce their climate impact.

The case study will be performed to calculate the greenhouse gas emission reduction potential of placing an A-trap including AD, AHPD or $AH_2PD$ compared to the baseline scenario. Gaasperdam produces 33,000 PE's of wastewater per day (de Fooij & Hofstede, 2019). In the current scenario, the wastewater of Gaasperdam goes towards the WWTP in Amsterdam-west which treats 906,184 PE's of wastewater per day (Waternet, 2015). In the new scenario, an A-trap will be placed at the sewage of Gaasperdam, after which the remaining wastewater goes to the WWTP in Amsterdam West. A schematic overview of the actual and assumed situation is given in Figure 12. The existing WWTP in Amsterdam will not be impacted significantly by the placement of an A-trap in Gaasperdam since it only removes a small part of the total PE's. Therefore, the WWTP in Amsterdam West keeps operating in the same way after placing the A-trap in Gaasperdam.

This research will make one assumption that helps to scale up the results. This assumption is that the A-trap will be placed at the location of the WWTP in Amsterdam west, treating 906,184 PE's of wastewater per day. Because of this assumption, the PST at the WWTP in Amsterdam West can be removed and the nitrification/denitrification process can change into the anammox process. This assumption helps to scale up the results of this study towards the scale of an entire WWTP. Furthermore, this assumption reveals the maximum potential of the AD, AHPD and $AH_2PD$ technology in combination with an A-trap.

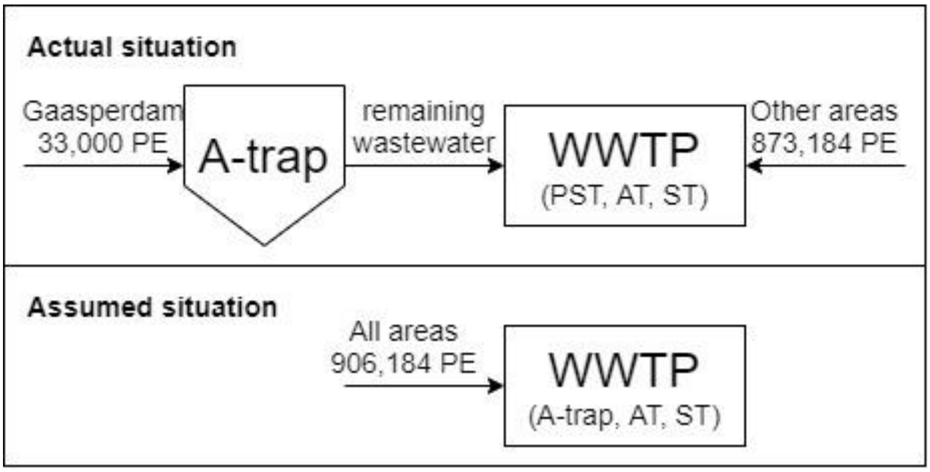


FIGURE 12: ASSUMPTION CASE STUDY

# 4. Method

The method section consists of the goal and scope of the research. This section deals with the functional unit, the system boundaries and the allocation procedure. This is followed by the data collection. Hereafter the methodology of the GHG emission calculation is explained. Lastly, the sensitivity analysis is introduced. This section helps to deal with the uncertainties in the LCA.

## 4.1 Research goal and scope

The goal of this research is to calculate the GHG reduction potential of the A-trap, AHPD and $AH_2PD$ scenarios. This is done by performing a cLCA on the GWP of different scenarios to treat the wastewater of Amsterdam West. A cLCA is suitable since changes are made to the technologies within the system. Answering the research questions will give insights into the current GHG emissions, and the GHG reduction potential of an A-trap with or without AHPD and $AH_2PD$, of the WWTP Amsterdam West. The different scenarios and their components are summarised underneath. Components which differ from the baseline scenario are <u>**underlined and bold**</u>. The $AH_{(x)}PD$ scenarios have two possible types of end-use of the digested sludge. The conservative scenario burns the digested sludge in a CHP. The optimistic scenario assumes that the metal concentration of the digested sludge is low enough to use the digested sludge as a fertiliser.

- Baseline scenario
    - Waterline: PST, AT and ST
    - Sludge line: AD, centrifuge, CHP
    - Biogas line: CHP and Torch (87% of the biogas is burned in a CHP, 13% of the biogas is burned in a torch)
- A-trap scenario
    - Waterline: <u>**A-trap**</u>, AT and ST
    - Sludge line: AD, centrifuge, CHP
    - Biogas line: CHP and Torch
- AHPD scenario
    - Waterline: <u>**A-trap**</u>, AT and ST
    - Sludge line: <u>**AHPD**</u>, <u>**CHP or fertiliser**</u>
      (The centrifuge is not needed anymore since the sludge is dewatered using the autogenerated pressure of $AH_{(x)}PD$. Depending on the concentration of heavy metals, the digested sludge can be used as a fertiliser, or must be burned in a CHP)
    - Biogas line: <u>**Biogas boiler**</u>**,** <u>**gas grid**</u>
      (The surplus gas is burned in a boiler, the biomethane is injected in the gas grid)
- $AH_2PD$ scenario
    - Waterline: <u>**A-trap**</u>, AT and ST
    - Sludge line: <u>**$AH_2PD$**</u>, <u>**CHP or fertiliser**</u>
      ($AH_2PD$ injects $H_2$ into the reactor, this reacts with $CO_2$ to form more biomethane. A conversion efficiency of 90% is used)
    - Biogas line: <u>**Biogas boiler**</u>**,** <u>**gas grid**</u>

It is important to be aware that the Technology Readiness Level (TRL) differs per technology. TRL's range from the observation of basic principles (TRL 1) to the prove of the actual system in an operational environment (TRL 9) (Mankins, 1995). All technologies in the baseline and A-trap scenarios are proven in an operational environment (TLR 9). The $AH_{(x)}PD$ technologies are tested in a pilot plant, in which the performance is demonstrated. This corresponds with a TLR level of 6. To make a comparison between the scenarios, it is assumed that the $AH_{(x)}PD$ will function in an operational environment. This assumption comes with additional uncertainties, which will be checked and discussed where possible.

## 4.1.1 Functional Unit

The GWP of the scenarios is compared based on one functional unit. The main function of a WWTP is to treat the incoming wastewater towards the pollutants are reduced in such a way that the effluent can be released to the surface water (Gallego et al., 2008). Based on this function, the following functional unit is defined:

**Functional unit:** “Processing all population equivalents* of the wastewater from the WWTP Amsterdam West until the water reaches surface water quality“

* Population Equivalent (PE) is a unit that describes an amount of wastewater produced. The unit is commonly used in literature about wastewater treatment and describes the oxygen demand needed to treat the wastewater of one average person per year. One PE traditionally equals 54 grams of BOD per person per day (Stora, 1985-4). However, WWTP’s report their PE’s based on the 150 grams of Total Oxygen Demand (TOD) per person per day (Stowa, 2014-09). \The PE definition used in this research is based on 150 grams of TOD per person per day. The WWTP in Amsterdam West treats 906,184 PE’s (Waternet, 2015). Gaasperdam contributes 33.000 PE’s to this wastewater (de Fooij & Hofstede, 2019).

## 4.1.2 System boundaries water-, sludge- and biogas line

The system boundaries used in this cLCA are from gate to grave. The input at the gate is wastewater which needs treatment and the output at the grave is surface water quality. The system boundaries are explained underneath in more detail.

The system boundaries of the waterline can be found in Figure 13. The bar screen and the grease removal are excluded from the system boundaries since their function is not influenced by replacing the PST for an A-Trap. The AT and ST are included in the system boundaries, since their function is influenced by placing an A-trap. This is because an A-trap removes more COD from the wastewater than a PST. This lowers the energy use of the AT and the ST. Furthermore, because there is less sludge at the AT, the process can change from nitrification-denitrification into the anammox process. This process uses less oxygen as explained in the case study description. Because of this, the electricity usage of supplying oxygen in the AT is reduced. As can be seen from Figure 13, the inputs of the process within the system boundaries consist of wastewater and electricity and the outputs of the process consist of $CO_2$, $CH_4$, $N_2O$ and $N_2$ emissions, surface water, sludge, and nitrogen.

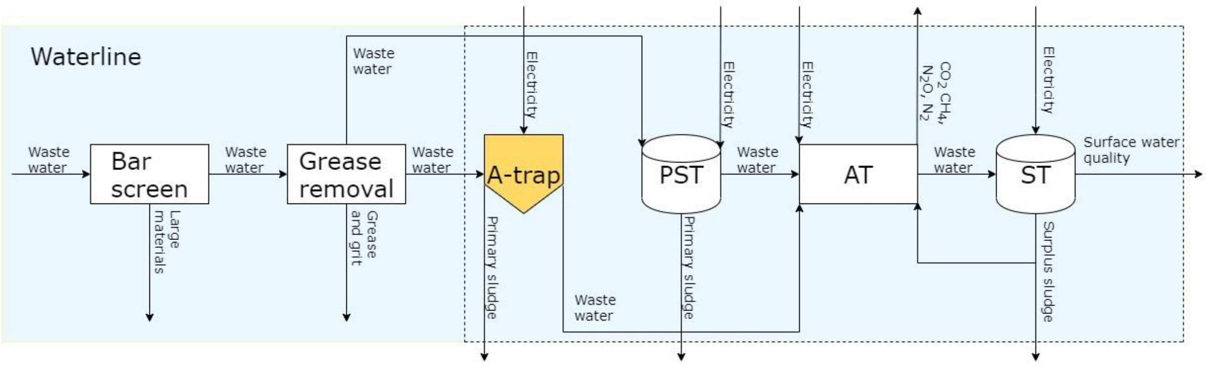


FIGURE 13: SYSTEM BOUNDARIES OF THE WATERLINE (INDICATED WITH DASHED LINE)

Two different sludge processing methods will be compared, which are AD and $AH_{(x)}PD$. The system boundaries of the AD process can be found in Figure 14. The yellow coloured boxes are optional and differ per WWTP. As can be seen from this figure, the upgrading of the biogas is excluded in the system boundaries. This is because most biogas from the AD process is burned directly in a CHP plant (CBS, 2018) and It would not be possible to cover both the upgrading and the CHP option within the timeframe of this research. Only 87% of the biogas is burned in a CHP, and 13% of the biogas is burned in a Torch (Waternet, 2015). This is not shown in the system boundaries, but this is included in this research. The sludge output of the AD process differs from that of the AHPD process. For example, the energy and water content of the sludge from the AD process is higher than that of the AHPD process. Furthermore, the sludge coming from the AD process still contains heavy metals (Waternet, 2015). The sludge of the WWTP in Amsterdam West is not dried after the centrifuge; therefore, the drying stage is not included in the flow chart. The inputs of the process and the sludge processing are sludge, electricity, heat, NG, polyelectrolyte (PE), $FeCL_3$. The outputs are $CO_2$ and $CH_4$ emissions, waste (Zn, Pb, Cu, and Hg), wastewater, electricity, heat, and Ash. The electricity and heat production of the CHP is allocated using substitution because it is not produced with AHPD. The polyelectrolyte (PE) and $FeCL_3$ input and the waste (Zn, Pb, Cu, and Hg) output are excluded from this research. The impact in GWP of these flows is estimated to be less than 1 percent since the concentrations are marginal. However, the impact of the waste (heavy metals) on the end-use of the digested sludge (CHP) is included.

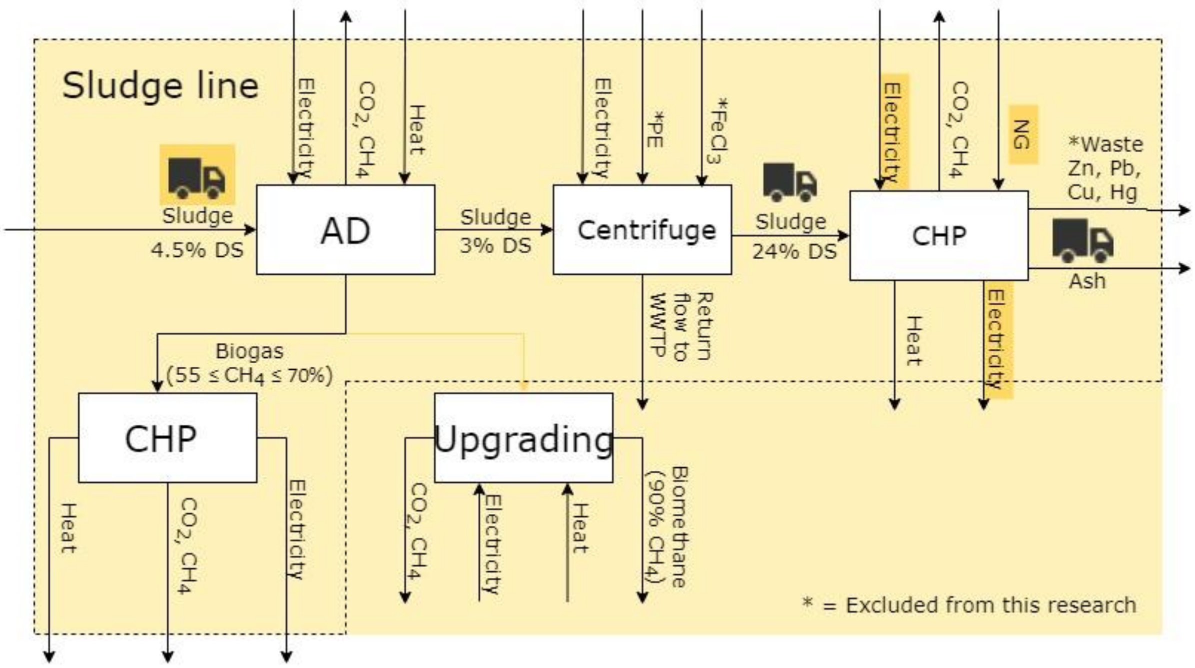


FIGURE 14: SYSTEM BOUNDARIES OF THE SLUDGE LINE USING AD (INDICATED WITH DASHED LINE)

The system boundaries of the sludge line using the $AH_{(x)}PD$ technology are displayed in Figure 15. Two types of end-use of the digested sludge are included in the system boundaries. Depending on the concentration of metals (which is currently unknown), it may be possible to use the digested sludge as a fertiliser. If the concentration exceeds the maximum concentration, the remaining sludge needs to be burned in a CHP. The inputs of the process are sludge, electricity, heat and depending on the DS percentage of the sludge NG. For $AH_2PD$ one of the inputs is also $H_2$. The benefit of injecting hydrogen is that the biogenic $CO_2$ coming from the process reacts towards methane, leading to a reduction in $CO_2$ emissions and an increase in gas production. However, there will only be a reduction in GHG emissions if the emissions of hydrogen production are low. The outputs of the process are Waste (Zn, Pb, Cu and Hg), $N_2$, surface water quality, biomethane, surplus gas (used in a boiler for heat production), $CO_2$ and $CH_4$ emissions, ash and depending on the end-use of the sludge fertiliser or electricity and heat. The biogenic emissions of the end-use of the biomethane is included in the system boundaries, despite the biomethane is injected into the gas grid. This is done because also the fossil emissions of the end-use of the NG are substituted (see the next section). It is assumed that the biomethane is completely combusted at its end-usage. The waste (Zn, Pb, Cu, and Hg) is excluded from the system boundaries because the impact in GWP is estimated to be below 1 percent since the concentrations are marginal. However, the impact of the waste (heavy metals) on the end-use of the digested sludge (CHP or Fertiliser) is included.

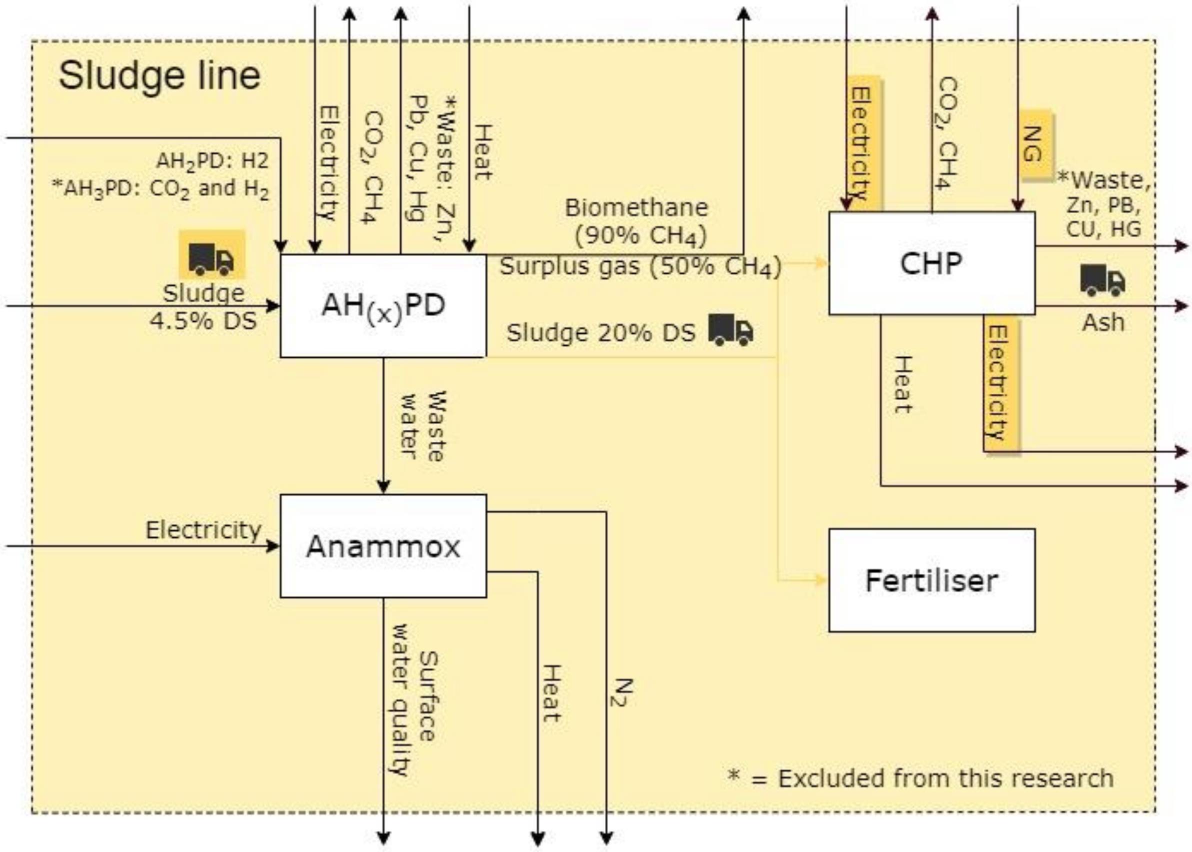


**FIGURE 15: SYSTEM BOUNDARIES OF THE SLUDGE LINE USING AH(x)PD (INDICATED WITH DASHED LINE)**

### 4.1.3 Allocation procedure

For this research mass allocation is used within the different processes shown in the flowcharts. This allocation procedure makes it possible to compare the different processes concerning the number of inputs (like electricity and heat) required to remove one unit of mass (COD). Mass allocation should be used in LCA if the impact category is impacted linearly by the amount of product delivered by a process (Baumann & Tilman, 2004). The GWP of the waterline is impacted linearly by the amount of COD in the incoming wastewater. Furthermore, the GWP of the sludge line depends linearly on the COD input from the incoming sludge towards the AD. Mass allocation based on COD flows is used to allocate the in- and outputs of the water- and sludge line (Section 5.3). Furthermore, this allocation procedure is used to calculate the internal sludge input to the WWTP Amsterdam west (section 5.4).

A different method of allocation is used to compare the GWP of the scenarios with each other. These scenarios all include several processes with their own in- and outputs. The end products of the AD process (electricity and heat) differ from the end products of the AH(x)PD processes (biomethane and fertiliser). It is best to avoid the allocation of the end products by increasing the detail in the model or by using system expansion. Both methods would increase the detail and complexity in the study in such a way that the timeframe of this research may become a problem. It can be argued that substitution provides compatible results as system expansion without the complexity of system expansion (Wardenaar et al., 2012). It is chosen to do the allocation of the end products based on substitution. The formula which is used for the substitution for the end products of the four scenarios is shown in Formula 9.

$$[\mathbf{9}]: E\ (Sub) = \ E\ (Biomethane) + \mathrm{E\ (Elec)} + \mathrm{E\ (Heat)} + \mathrm{E\ (Fert)}$$

**Where:**

E (Sub) = GHG emissions which need to be substituted
E (Biomethane) = GHG Emissions of pressurising and combusting fossil Natural Gas
E (Elec) = GHG emissions of the production of electricity in the Netherlands using the marginal Dutch electricity mix.
E (Heat) = GHG emissions of the production of heat using natural gas
E (Fert) = GHG emissions of the production of an alternative amount of fertiliser with the same function.

## 4.2 GHG emissions calculations

The GHG emissions of all processes occurring within the system boundaries are calculated in this research. The GHG emissions which are included in this research are $CO_2$, $CH_4$, and $N_2O$. The conversion factors into $CO_2$-eq of those GHG's are: 1 $CO_2$ = 1 $CO_2$-eq, 1 $CH_4$ = 25 $CO_2$-eq and 1 $N_2O$ = 298 $CO_2$-eq (Winnipeg, 2012). These conversion factors are based on a time horizon of 100 years.

It is a common practice in the LCA community and recommended by the IPCC, to not count biogenic $CO_2$ emissions (Rabl et al., 2007). The argument behind this is that as many emissions are emitted during the combustion, as removed during the growth of the biomass. This practice is also done in many current studies of wastewater treatment and sludge processing. The consequence of this approach is that no attention has so far been given to biogenic $CO_2$ emissions, these are largely unknown, and waterboards do not have any emission reduction targets for biogenic $CO_2$. This research includes fossil and biogenic $CO_2$ emissions. Different digestion methods (AD, AHPD, and $AH_2PD$) can prevent some of the biogenic $CO_2$ emissions by converting biogenic carbon towards useful end-products, like heat, electricity, and biomethane. Therefore, including biogenic $CO_2$ gives additional insights into the GHG reduction potential of CCU, which differs between the scenarios. One should be aware that the biogenic emissions of the end-use of biomethane are also included in this research, despite the biomethane is injected into the gas grid. It is assumed that the biomethane is completely combusted at its end-usage. This is done since the GHG reduction would otherwise be counted double when substituting fossil GHG emissions from NG. Because it is uncommon to include biogenic $CO_2$ emissions, the biogenic $CO_2$ emissions are listed separately in the summary of the results (section 6.5). Furthermore, the results of all scenarios are also calculated without biogenic $CO_2$ in combination with two different allocation methods (substitution and exergy). This can be found in the sensitivity analysis in section 7.2.4 and 7.2.5.

The GHG emissions of the different scenarios are calculated based on scope 1 and scope 2 emissions. Scope 1 emissions are direct emissions coming from sources owned and controlled by waterboards. Scope 2 emissions are indirect emissions coming from the energy use of the waterboard and emission savings of the different end products. AD produces heat and electricity while $AH_{(x)}PD$ produces heat, biomethane and depending on the end-use of the sludge also fertiliser. As explained in section 4.1.3, allocation based on substitution is used in this research. Scope 3 emissions are not included in this research. These are indirect emissions, other than energy use, which are emitted because of activities of a WWTP or sludge processing method. The included emissions are summarised in Table 2

**TABLE 2: INCLUDED GHG EMISSIONS**

| | |
|---|---|
| **Scope 1** | Emissions of feedstock supply ($E_{fs}$) |
| | Emissions from processing ($E_p$) |
| | Emissions from transportation ($E_t$) |
| | Emissions from disposal of waste WWTP ($E_d$) |
| **Scope 2** | Emissions from energy usage WWTP and sludge processing ($E_{eu}$) |
| | Emission savings from produced products compared with the alternative ($E_{sub}$) |

The total GHG emissions are calculated using Formula 10. All GHG emissions are calculated per year for the WWTP Amsterdam West. This thesis is structured in such a way that the GWP can be calculated based on one simple calculation. This calculation uses the sub results of the emission factors (section 5.2), Mass and energy flows (section 5.3) and allocation factors (section 5.4).

$$[\mathbf{10}]: Basic\ calculation\ leading\ to\ the\ GHG\ gas\ emissions\ of\ the\ WWTP\ Amsterdam\ West = Emission\ factor\ in\ CO2 - eq\ (5.2) * Mass\ and\ energy\ flows\ (5.3) * allocation\ factor\ (5.4) * days\ per\ year$$

Based on the GWP of the entire WWTP Amsterdam West, the GWP of Gaasperdam is estimated. This estimation takes place based on the difference in PE's treated in Gaasperdam (33,000 PE's) and Amsterdam West (906,184 PE's). Literature was used to search for a scaling factor for WWTP's, however, this search was unsuccessful. Because of this, two different scaling factors are used to calculate the GWP of Gaasperdam. The GWP is scaled linearly (scaling factor 1) and exponential (scaling factor 0.7). The calculation of the scaling of the GWP of Gaasperdam can be found in Formula 11. Based on both scaling factors, it is assumed that the GWP of Gaasperdam is between 3.64% ad 9,84% of the GWP of the WWTP Amsterdam West.

$$[\mathbf{11}]: Scaling\ GWP\ Gaarperdam = \frac{\text{PE gaasperdam}}{\text{PE amsterdam west}}^{Scale\ factor} = \frac{33{,}000}{906{,}184}^{1\ or\ 0.7} = 3.64\%\ or\ 9.84\%$$

## 4.3 Data collection

The data collection consists of the collection of foreground and background data. Foreground data describes typically a specific product and production system, while background data consist of information about materials, energy, transport and waste management (Clift et al., 2000). The foreground data is gained through a combination of scientific literature, grey literature, and communication with Bareau and Waternet. Part of the data provided by Bareau and Waternet is based on a confidential database. The database of Bareau uses as inputs the results of their test reactor, scientific literature and grey literature from Stowa. If information from this internal database is used, it is referred to as Bareau, 2020. The database of Waternet contained detailed information about the in- and outputs of the WWTP located in Amsterdam West for the year 2015. The information gained from this model is referred to as Waternet, 2015. The background data is provided by Simapro and scientific literature. Simapro program consists of a user interface, a life cycle unit process database, an impact assessment database and a calculator that combines the numbers from the databases with the modelling of the product system (Hermann & Moltesen, 2015). This research uses the ecoinvent databases of Simapro for the modelling of the data in Excel. This choice is made because of the visualisation of the results is more modern in Excel, contributing to a better presentation of the results. Furthermore, Excel is better suited to model the mass and energy flows of a WWTP.

## 4.4 Sensitivity analysis

Two types of sensitivity analyses are performed. First, one sensitivity analysis is performed on the uncertain input parameters. Hereafter a sensitivity analysis is performed on the effect of different modelling assumptions on the results.

### 4.4.1 Sensitivity analysis on uncertain input parameters

This sensitivity analysis is performed on uncertain input parameters. These parameters are selected based on the degree that they can influence the result or contribute to the variance in the output. The sensitivity analysis will indicate the uncertain factors of the research, which can help to indicate the direction of further research to eliminate these uncertainties (Groen et al., 2014). There are different methods for sensitivity analysis in an LCA; One-at-a-time, Matrix perturbation, Method of elementary effects, Key issue analysis, Standardised regression coefficient, Random balance design or Sobols sensitivity index (Groen et al., 2014). This research will make use of a One-at-a-time sensitivity analysis. The benefit of this type of sensitivity analysis is that it is easy to perform and to understand for the reader. The sensitivity analysis will be performed using Excel and visualised using spider diagrams. These diagrams show the percentage of change of a parameter on the X-axis and the $CO_2$-eq emissions on the Y-axis. The uncertainty is ranged by a percentage on a four-point scale. If the uncertainty is small, the initial value of the parameter is ranged from -25% towards +25%. The values of the parameters with bigger uncertainties are ranged by 50%, 75% or 100%. The uncertainty in some parameters is sometimes certain. E.g. in the case if literature indicates that the value of a parameter ranges between two values. In this case, this range is taken instead of the four-point scale. The uncertain parameters, their range and the reason for the uncertainty are given in Table 3.

**TABLE 3: SENSITIVITY ANALYSIS ON INPUT PARAMETERS**

| Parameter | Range | Reason for the uncertainty |
| --- | --- | --- |
| Electricity and heat usage (Baseline and A-trap scenario) | -25% → +25% | The electricity usage is partly based on literature, which can differ from the actual situation. The heat usage of the digestor depends on external factors like the outside temperature. Therefore, heat usage can differ from year to year. It is expected that the uncertainty keeps within a 25% range. |
| Electricity and heat usage (AHPD and $AH_2PD$ scenario) | -25% → +100% | The same reasons are valid as mentioned above. Furthermore, there is an additional uncertainty because no full-scale AHPD or $AH_2PD$ installation already exists and the electricity and heat usage of $AH_{(x)}PD$ is based on a model of Bareau which could not be verified. To test the robustness of the results, this parameter is ranged from -25% to +100%. |
| Transportation distance | -50% → +50% | Part of the transportation distance is estimated. It is expected that the actual distance keeps between a 50% interval. |
| $CO_2$-eq emissions $H_2$ production | -100% → +200% | Despite the production of green hydrogen is limited (Dincer & Acar, 2015), the usage of hydrogen from PV electrolysis is assumed in this research. If the electricity is produced by (excess) green electricity, it is assumed that there are no emissions (-100% scenario). Most hydrogen is produced with fossil fuel reforming, which emits 200% more $CO_2$-eq emissions than PV electrolyses (See Table 6) |

| | | |
|---|---|---|
| $N_2O$ emissions | 0% → +2857% | All WWTP's report their $N_2O$ emissions based on one study from 1993 of a small WWTP in Durham (Kampschreur et al., 2009). This study measured 3.2 g $N_2O$ emissions per PE per year, corresponding with 0.035% of the incoming nitrogen load (Czepiel et al., 1995). These emissions can incidentally be as much as 95% of the incoming nitrogen load, however most measurements indicate emissions below 1% of the incoming nitrogen load (Kampschreur et al., 2009). This research ranges the emissions until 1% of the incoming nitrogen load, with corresponds with an increase of (1 (%) / 0.035 (%) * 100 (%)) = 2857%. |
| COD removal efficiency A-trap | -28%% → +22% | This research uses the best performing A-trap in the Netherlands (Dokhaven) with a COD removal efficiency of 74% (KNW, 2017). The worst performing A-trap in the Netherlands has a COD removal efficiency of 53% and is in Nieuwveer (KNW). Theoretically, an A-trap can have a COD removal efficiency of 90% (K. Zagt, personal communication, June 20, 2019). The COD removal efficiency is ranged from 53% to 90%. This corresponds with a decrease of 28% and an increase of 22%. |

### 4.4.2 Sensitivity analysis on modelling assumptions

This sensitivity analysis is performed to check what will happen to the GWP of the different scenarios in case of a different modelling assumption. Four modelling assumptions (and one combination of modelling assumptions) are changed, which are shown in Table 4. The GWP of all scenarios will be shown in a bar chart for each new modelling assumption.

**TABLE 4: SENSITIVITY ANALYSIS ON MODELLING ASSUMPTIONS**

| Modelling assumption | Current assumption | New assumption |
|---|---|---|
| Allocation method | Based on substitution | Based on exergy |
| Biogas usage baseline and A-trap scenario | 87% in a CHP<br>13% in a torch | 100% in a CHP<br>0% in a torch |
| Crediting of excess heat | No | Yes |
| Including biogenic $CO_2$ emissions | Yes | No |
| Allocation method<br>Including biogenic $CO_2$ emissions | Based on substitution<br>Yes | Based on exergy<br>No |

Changing the allocation method of the end products to exergy allocation needs explaining. Exergy can be defined as the amount of work that can be extracted from the energy carrier (Chen et al., 2009). The allocation based on energy is based on the calculation in Formula 12. The exergy in biomethane, electricity, natural gas, and hydrogen equals the energy (Gong & wall, 2016; Blok & Nieuwlaar, 2016). The exergy in the heat depends on the temperature. More work can be extracted from higher temperature heat, resulting in a higher exergy factor. It is assumed that the temperature of all the used heat is 120 ◦C. Based on this assumption, the exergy in the heat is 0.15 times the energy in the heat. (Blok & Nieuwlaar, 2016).

$$[\mathbf{12}]: \frac{GWP\ (\frac{kg\ CO2-eq}{year})}{Sum\ exergy\ (biomethane + heat\ \pm electricity - natural\ gas\ - hydrogen)\ (\frac{GJ}{year})}$$

# 5. Inventory analysis and modelling assumptions

The inventory analysis consists of the conversion and emission factors, all mass and energy flows and the calculation of the different allocation factors.

## 5.1 Conversion factors and measurements

The important conversion factors used in this research are listed in Table 5. Furthermore, this table lists the gas composition of AHPD and $AH_2PD$, which is based on measurements. All produced $CO_2$ during $AH_{(x)}PD$, which is not present in either the biomethane or the surplus gas is dissolved in the liquid. Some conversion factors need further explaining or calculations, this can be found at the corresponding number under the table.

**TABLE 5: CONVERSION FACTORS AND MEASUREMENTS**

| Conversion | Factor | Source |
|---|---|---|
| COD removal efficiency A-trap | 1 74% | (KNW, 2017) |
| From ODS to COD | * 1.42 | 2 (Stora, 1981-16) |
| From ODS in primary sludge to Biogas (From the PST and A-trap) | 3 1,100 nM3 / tonne ODS removed | (Stowa, 2011-16) |
| From ODS in surplus sludge to Biogas (From the ST) | 3 700 nM3 / tonne ODS removed | (Stowa, 2011-16) |
| Correction factor gas production | * 0.89 | (Appendix 1.1, calculation nr 1) |
| Gas composition biogas from the WWTP Amsterdam West | 60% $CH_4$, 40% $CO_2$ | (Waternet, 2015) |
| Standard gas composition broken down ODS (Used for AHPD and $AH_2PD$) | 4 64% $CH_4$, 36% $CO_2$ | (Stowa, 2011-16; Bareau, 2020) |
| % of ODS converted during AD | 46% | (Waternet, 2019) |
| % of ODS converted during AHPD and $AH_2PD$ | 60% | (Appendix 1.1, calculation nr 2, 3 and 4) |
| Gas composition AHPD | Biomethane: 90% $CH_4$, 10% $CO_2$<br>Surplus gas: 53% $CH_4$, 47% $CO_2$ | (Bareau, 2020) |
| Gas composition $AH_2PD$ | 5 Biomethane: 95% $CH_4$, 5% $CO_2$<br>Surplus gas: 55% $CH_4$, 45% $CO_2$ | (Bareau, 2020) |
| Efficiency conversion $H_2$ to $CH_4$ | 90% | (Bareau, 2020) |
| % of $CO_2$ converted to $CH_4$ during $AH_2PD$ | 50% | (Bareau, 2020) |
| % of total methane in the biomethane AHPD and $AH_2PD$ (rest in surplus gas) | 89% | (Bareau, 2020) |

1 Literature shows that A-traps can differ a lot in their COD removal efficiency. E.g. an existing A-trap in Nieuwveer removes 53% of the COD, while an existing A-trap in Dokhaven removes 74% of the COD (KNW, 2017). This research uses the state-of-the-art COD removal efficiency.

2 The source of this conversion factor is based on a publication from 1981. Even though this is outdated, this value is still used in more modern reports. It is common to use the term COD for the waterline and the term ODS for the sludge line.

[3]Primary sludge (from the PST or A-trap) produces 1100 nM3/tonne ODS removed and surplus sludge (from the ST) produces 700 nM3/tonne ODS removed (Stowa, 2011-16). According to Agentschap NL (2010), the biogas production is between 800 and 1100 nM3/tonne ODS removed. The research is in line with the Stowa report but cannot be used since it does not subdivide the production from primary and surplus sludge. A critical report from Witteveen & Bos argues that the biogas production should be lower than the values reported by Stowa (De Fooij & Hofstede, 2019). This research has checked the conversion parameter from removed ODS towards biogas. This is done by comparing the measured biogas production in the baseline scenario with the expected biogas production using the biogas production defined in Stowa (2011-16). A correction parameter for the values of Stowa (2011-16) is calculated in appendix 1.1.1, which makes the gas production of literature match the measurements. This helps to make the values of literature more accurate, before using it to calculate the biogas production of AD, AHPD or $AH_2PD$ in combination with an A-trap.

[4]According to Stowa (2011-16) the biogas concentration is on average 63% $CH_4$ and 35% $CO_2$. The other 2% of the average gas production is $H_2O$. Measurements show that the gas produced by Bareau does not contain water (Bareau, 2020). Therefore, the assumption is made that 64% of the biogas consist of $CH_4$ and 36% of the biogas consist of $CO_2$.

[5]The measurements of the gas concentrations during $AH_2PD$ are based on a reactor pressure of 20 bars. However, a new idea of Bareau is to reduce the pressure of $AH_2PD$ to 8 bars (K. Zagt, personal communication, February 26, 2019). There were no measurements of the gas concentrations at 8 bars and therefore the measurements at 20 bars are used. In practice, the $CH_4$ concentration is likely to decrease in the biomethane and the amount of surplus gas is likely to reduce since less $CO_2$ and $CH_4$ will dissolve.

## 5.2 Emission factors

The emission factors of the different processes occurring in wastewater treatment and sludge processing are listed in Table 6. If possible, the $CO_2$ and $CH_4$ emissions are listed separately, otherwise, the $CO_2$-eq emissions are given. $N_2O$ emissions only occur in the AT and are not based on measurements. The best estimation of the $N_2O$ emissions in the AT during the nitrification /denitrification process are 3.2 g/PE removed per year (Stowa, 2014-09). For the anammox process, the same value is assumed. All calculations can be found in Appendix 1.2, under the corresponding calculation numbers (indicated as [..]).

The emissions for hydrogen production are debatable. Around 80% of the worldwide hydrogen demand is produced by the reforming of gas or oil (Dincer & Acar, 2015). Only 3.9% of the hydrogen demand is produced by electrolysis since it cannot reach high conversion efficiencies and it is one of the more expensive methods (Dincer & Acar, 2015). Electrolyses can be based on grey or green electricity. The emissions of H2 production are calculated based on PV electrolysis. The sensitivity analysis will check the impact of fossil fuel reforming, and emission-free hydrogen.

**TABLE 6: EMISSION FACTORS**

| Parameter | $CO_2$ | $CH_4$ | $CO_2$-eq | Unit | Source |
|---|---|---|---|---|---|
| **Processes** | | | | | |
| Biological COD removal (PST scenario) | [1]1,200 | | | $\frac{g}{kg\ COD\ removed}$ | (Stowa, 2014-09) |
| Biological COD removal (A-trap scenario) | [2]947 [2] | | | $\frac{g}{kg\ COD\ removed}$ | [2](Stowa, 2014-09) |

| | | | | | |
|---|---|---|---|---|---|
| $CH_4$ emissions waterline<br>(From the AT and the effluent) | | 8.75 | | $\frac{g}{kg\ COD\ removed}$ | (Stowa, 2014-09) |
| $CH_4$ emissions sludge line<br>(AD scenarios,<br>from thickeners and buffers) | | 27.8 | | $\frac{g}{nM3\ biogas}$ | (Stowa, 2014-09) |
| $CH_4$ emissions sludge line<br>(AHPD and $AH_2PD$ scenario,<br>from thickeners and buffers) | | [3]13.9 | | $\frac{g}{nM3\ biogas}$ | [3](Stowa, 2014-09) |
| **Fuels** | | | | | |
| Biogas<br>(Burned in torch**)** | [4]1,941<br>[3] | 7.48 | | $\frac{g}{nM3\ biogas}$ | (Stowa, 2014-09) |
| Biogas<br>(Burned in CHP) | [4]1,936<br>[4] | 9.36 | | $\frac{g}{nM3\ biogas}$ | (Stowa, 2014-09) |
| Surplus gas<br>(Burned in boiler) | [4]1,944<br>[5&6] | 7.48 | | $\frac{g}{nM3\ surplus\ gas}$ | (Stowa, 2014-09) |
| NG or biomethane (complete) combustion | | | [5]1,795<br>[7] | $\frac{g}{nM3\ NG/bioCH4}$ | (Vreuls & Zijlema, 2009) |
| NG pressurisation | | | 62.4<br>[8] | $\frac{g}{nM3\ NG}$ | (RVO, 2011) |
| Diesel<br>(Truck 16 tonne) | 346 | 0.53 | | $\frac{g}{tonne\ km}$ | (ETH-ESU, 1996) |
| $H_2$<br>(PV electrolysis) | | | [6]3,000 | $\frac{g}{kg\ H2}$ | (Dincer & Acar, 2015) |
| $H_2$<br>(Fossil fuel reforming) | | | [6]9,000 | $\frac{g}{kg\ H2}$ | (Dincer & Acar, 2015) |
| **Electricity and heat** | | | | | |
| Electricity | | | 480 | $\frac{g}{kWh}$ | (CBS, 2013) |
| Heat<br>(Usage > production) | | | 80.0 | $\frac{g}{MJ}$ | (EC, 2017) |
| Heat<br>(Usage < production) | | | [7]0 | $\frac{g}{MJ}$ | |
| **Chemicals** | | | | | |
| Fertiliser<br>(Production avoided by sludge) | | | 343 | $\frac{g}{tonne\ ds}$ | (Liu et al., 2013) |

[1]The $CO_2$ emissions depend on the composition of the COD. Waterboards report these biological emissions based on average values, which is 1,200 g $CO_2$/kg COD removed according to Stowa (2014-09).

[2]In the case of an A-trap, there will be more primary sludge and less surplus sludge. More gas is produced per kg COD removed from primary sludge as from surplus sludge. As a result, less carbon remains in the sludge which influences the emission factor. The new emission factor is based on the old one from Stowa (2014-09) and calculated in Appendix 1. This calculation is based on the carbon balance, which should be the same for the baseline and A-trap scenario.

[3]The $CH_4$ emissions are mainly emitted in the two thickeners (Stowa, 2014-09). With $AH_{(x)}PD$, one of the thickeners is integrated into the AHPD reactor. Therefore, less $CH_4$ emissions are emitted into the air. It is assumed that the emission factor for $AH_{(x)}PD$ is half of the original one. Based on the definition of this emission factor, the $CH_4$ emissions from $AH_2PD$ would be higher than that of AHPD. This is

caused by the increased gas production by the hydrogen injection. Since the $CH_4$ emissions in the thickeners will not change because of this, the $AH_2PD$ scenario is credited with the same $CH_4$ emissions in the sludge line as the AHPD scenario.

4The $CH_4$ emissions are reported by Stowa (2014-09) and the $CO_2$ emissions are calculated.

5This emission factor is used to include the biogenic emissions of the combustion of biomethane. Furthermore, this emission factor is used to include the emissions of NG usage and the avoided fossil emissions by combusting biomethane instead of NG.

6The emission factors of $H_2$ production has some uncertainty. Ozbilen (2010) indicated the $CO_2$-eq of $H_2$ production to be 2250 g $CO_2$-eq/kg $H_2$ for PV electrolysis and 11,950 g $CO_2$-eq/kg $H_2$ for fossil fuel reforming. The emission factor of Dincer & Ancer (2015) is used in this research because it has more citations and the publication is more recent.

7Excess heat of waterboards is often wasted (K. Zagt, personal communication, June 7, 2019). Therefore, the overproduction of heat is not credited with a negative emission factor.

## 5.3 Process flowcharts and detailed assumptions

This section shows the mass and energy flows within the water- sludge- and biogas line for the WWTP Amsterdam West. External sludge is added to the AD installation in the sludge line. Not only the sludge line is affected by this external flow since part of the external flow researches the waterline through the return flow, and more biogas is produced because of the increased sludge input. All flowcharts need to be allocated to fit the different scenarios. This allocation takes place in the next chapter (5.4).

### 5.3.1 Flowcharts for the waterline

Figure 16 shows the mass and energy flows of the waterline containing a PST. This figure shows all COD, water, electricity, and heat flows for the waterline of the baseline scenario. As can be seen in the figure total water input of the waterline is 178*$10^3$ m3/d. Total water output to the surface water is 176*$10^3$ m3/d and the rest remains in the sludge. Total COD input is 109 tonne/d. From this input 86 tonne/d goes to the sludge line, 16 tonne/d is aerated, and 7 tonne/d is released into the surface water. The total heat usage is 5.0 GJ/d, which is caused by the heat demand of the buildings. Total electricity usage is 47 MWh/d. Most of this electricity is used for the supply of oxygen in the AT tank (22 MWh/d) and to pump the wastewater through the entire system (15 MWh/d from the 17 MWh/d fixed electricity usage). All calculations for the COD and water flows can be found in Appendix 2.1. The calculations for the heat and electricity usage can be found in Appendix 4.2.1 and 4.2.2.

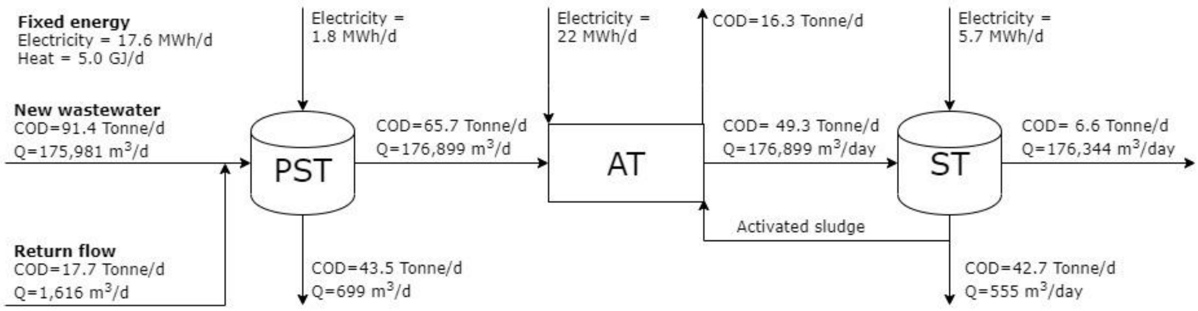


**FIGURE 16: MASS AND ENERGY FLOWS OF THE WATERLINE WITH A PST**

Figure 17 shows the mass and energy flows of the waterline for the A-trap scenario. For the AHPD and $AH_2PD$ scenario, the same flowchart is used. However, the mass and energy flows are different because there is no return flow is these scenarios. The difference in COD input is dealt with in the allocation section, which makes this Figure suitable for all scenarios consisting of an A-trap.

The wastewater input is slightly higher (299 $m^3$/d) than in the PST scenario, which is caused by the increased return flow from the centrifuge. More water goes towards the sludge line since more sludge is captured in this scenario. The water output from the ST to surface water is similar in both scenarios. The COD output from the A-trap increases by 38.8 tonne/d compared to the PST. This is caused by the increased removal efficiency, which was 40% for the PST (Waternet, 2015) and is 74% for the A-trap (KNW, 2017). As a result, the COD aerated, the COD output from the ST to the sludge line and the COD outputs towards the surface water decreases. The increasing COD flow to the sludge line causes an increase in the return flow from the centrifuge. The total heat demand is due to the heat demand of the buildings. The total electricity usage in this scenario is 42.2 MWh/d. This is a decrease of 4.9 MWh/d compared to the PST scenario. The electricity inputs for A-trap, AT, and ST differ in the new scenario. The electricity usage of the A-trap increases compared to the PST scenario since an A-trap is aerated. The electricity usage of the ST decreases since the COD input to the ST lowers. The electricity usage of the AT decreases because the total oxygen demand decreases. The TOD is a combination of the COD and the oxygen needed for nitrogen removal. There are two reasons why the TOD decreases in de new scenario:

1. The breakdown of COD in the AT reduces proportional to the reduction of the COD input towards the AT.
2. The nitrogen removal process changes from nitrification/denitrification into the anammox process in case of an A-trap. This process requires 1.5 mol oxygen per mol nitrogen removed, while the nitrification/denitrification process requires 4.0 mol oxygen per mol nitrogen removed. Conventional WWTP removes 58% of the incoming nitrogen load in the AT (Mininni et al., 2015). It is assumed that this percentage is the same for the PST and the A-trap situation. Both factors result in a reduction of the electricity usage for the A-trap situation. The new electricity usage is calculated to be 8.9 MWh/d.

The calculations for the new COD flows can be found in Appendix 2.2. The calculations for the new water flows can be found in Appendix 2.3. The heat flows can be found in Appendix 4.1.2 and the electricity flows can be found in Appendix 4.2.2.

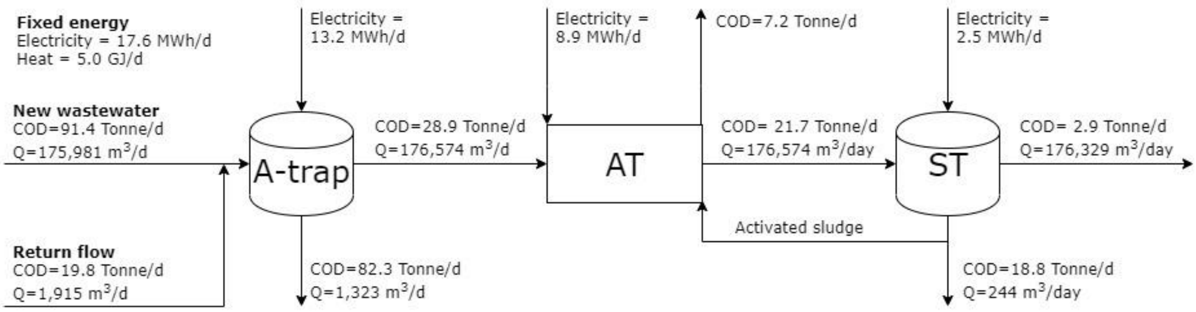


**FIGURE 17: MASS AND ENERGY FLOWS OF THE WATERLINE WITH AN A-TRAP**

## 5.3.2 Flowcharts for the sludge line

Figure 18 shows the mass and energy flows for the sludge line for the baseline scenario. The flowchart for the A-trap scenario is similar but has an increased ODS and IDS input from the waterline. The mass and energy flows for the sludge line of the A-trap scenario are also calculated in the appendix (section 3.2, 3.4, 4.1.2, 4.2.2 and 4.3.1). However, they are not notated in the flowchart because the flowchart almost looks the same way. One important assumption between the two scenarios is that the $CH_4$ and

$CO_2$ concentration of the biogas remains the same when more primary sludge and less surplus sludge is added to the AD, in case of the A-trap. This assumption is in line with reported gas concentrations in Stowa (2014-09).

As can be seen in the figure, the total ODS input to the AD is 88.9 tonne/d. This ODS is converted for 40% into biogas and the remaining ODS (48.2 tonne/d) goes towards the centrifuge. The centrifuge removes 25% of the incoming ODS which is an input to the waterline (trough the return flow). The remaining ODS goes towards the CHP at AEB which burns it. The IDS input to AD is 22.2 tonne/d. Since the DS is inorganic, it is not digested in the AD and the entire flow goes to the centrifuge. The centrifuge removes 25% of the IDS and the remaining 16.1 tonne goes towards the CHP at AEB, leading to the output of ash. The average water content of the incoming sludge is 6%. Because ODS is removed in the AD, the water content is increased towards 3.8%. The centrifuge dries the sludge towards 22.4% ds, which leads to a water flow (the return flow) of 1616 $m^3$/d. The CHP at AEB removes all the remaining water. The biogas production of AD is 32 * $10^3$ $nM^3$ per day. This gas consists for 39.9% of $CO_2$ and 59.9% of $CH_4$. The NG consumption at AEB is a result of the heat demand to dry the sludge until it burns. Two processes use heat, which are the buildings (5 GJ/d) and the AD (113 GJ/d). The CHP at AEB produces 37 GJ of heat per day. The total electricity usage of the sludge line is 18.3 MWh/d. The majority of this electricity (10.2 MWh/d) is consumed at the CHP at AEB. Lastly, two processes require transport. First, the sludge is transported from the centrifuge towards the CHP at AEB over a distance of 2.2 km. Hereafter the ash coming from the CHP (which is mostly used in concrete production) is transported over an estimated distance of 50km. The calculation for the sludge flows can be found in Appendix 3.1. The calculations for the transportation can be found in Appendix 3.4. The calculations for the heat electricity usage can be found in Appendix 4.1.1 and 4.2.1. Lastly, the calculations for the biogas production and NG usage can be found in appendix 4.3.1.

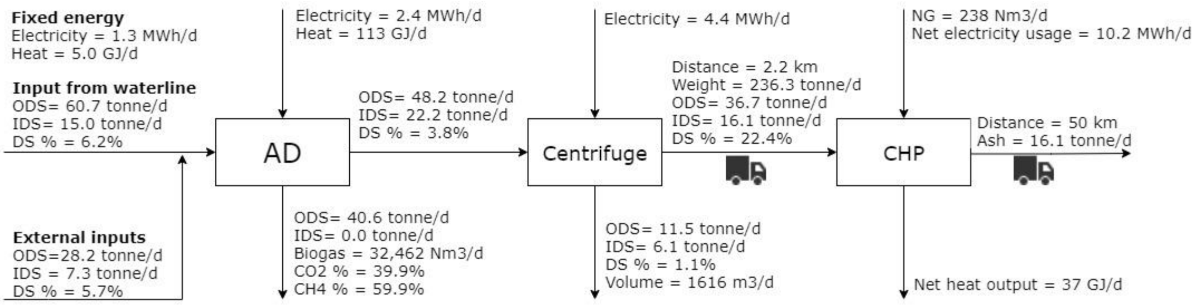


**FIGURE 18: MASS AND ENERGY FLOWS OF THE SLUDGE LINE WITH AD**

The mass and energy flows of the sludge line of the AHPD scenario can be found in Figure 19. The mass and energy inputs produced by the A-trap in the AD scenario is used in this flowchart. However, since AHPD has no return flow, the input towards the waterline decreases, which also leads to lower sludge outputs towards AHPD. This difference is dealt with during the allocation.

The ODS input to AHPD is 71.2 tonne/d. This ODS converts for 60% towards biogas, the remaining 28.5 tonne ODS/d goes towards the CHP at AEB or is used as a nitrogen/phosphor fertiliser. The DS% of the incoming sludge is 5.6% and the DS% of the outgoing sludge is around 20%. This leads to a water flow of 1093 $m^3$/d from the AHPD, which is treated in an anammox installation until the nitrogen concentration is low enough to release the water to the surface. The biomethane production of AHPD is calculated to be 25 * $10^3$ $nM^3$/d. This gas has a methane content of 90%. Also, 5 * $10^3$ $nM^3$/d of surplus gas (containing 52.6% methane) is produced during. Because of the 20 bars of pressure, 9 * $10^3$ $nM^3$ of carbon dioxide dissolves into the water phase per day. Depending on the end-use of the sludge, there is an NG consumption of 200 $Nm^3$/d (In case of the CHP at AEB). The heat consumption of AHPD is 65 GJ/d and the heat consumption of the buildings is 5 GJ/d. The heat consumption of AHPD is lower than that of AD because of the better insulation. In case the sludge is burned at the CHP at AEB, there is a heat production of 31 GJ/d. The total electricity usage is between 9.4 MWh/d and 18.0 MWh/d depending on the end-use of the sludge. Most of the electricity is used during AHPD (6.7 MWh/d) and depending on the end-use of the sludge in the CHP at AEB (8.6 MWh/d). The transportation distance of the sludge used in agriculture as a fertiliser is assumed to be 50 km. The transportation distance of the sludge towards AEB is 2.2 km. The remaining ash of AEB is assumed to be transported over 50 km. The calculation for the sludge flows can be found in Appendix 3.3. The calculations for the transportation can be found in Appendix 3.4. The calculations for the heat and electricity usage can be found in Appendix 4.1.3 and 4.2.3. Lastly, the calculations for the production of biomethane and surplus gas and the usage of NG can be found in appendix 4.3.2.

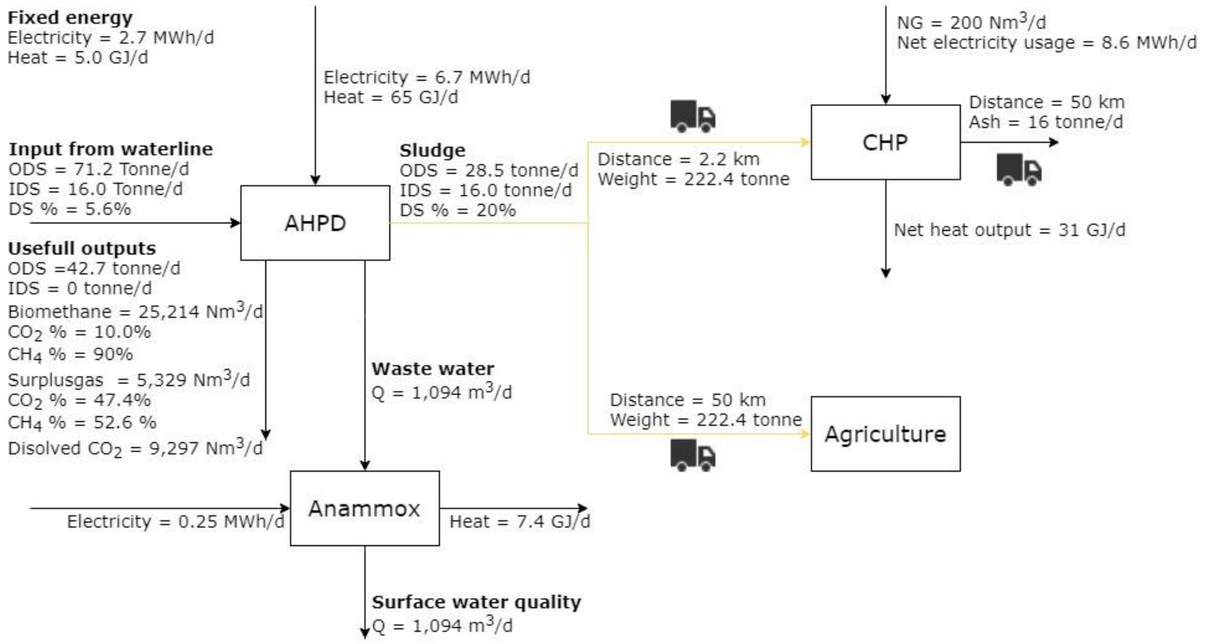


FIGURE 19: MASS AND ENERGY FLOWS OF THE SLUDGE LINE WITH AHPD

The mass and energy flows of $AH_2PD$ are shown in Figure 20. The mass and energy inputs produced by the A-trap in the A-trap scenario is used in this flowchart. However, since $AH_2PD$ has no return flow, the input towards the waterline decreases, which also leads to lower sludge outputs towards AHPD. This difference is dealt with in the allocation. The differences between AHPD and $AH_2PD$ are explained below.

The injected hydrogen (2.8 tonne/d) reacts with the carbon dioxide in the reactor and increases the biomethane and surplus gas production. The new biomethane production is 30 * $10^3$ $nM^3$/d. This gas consists of 94.6% of methane and 5.4% of carbon dioxide (Bareau, 2020). The surplus gas production increases towards 7* $10^3$ $nM^3$/d. This gas consists for 55% of methane and 45% of carbon dioxide (Bareau, 2020). Since the carbon dioxide reacts with the hydrogen, less carbon dioxide (3 * $10^3$ $nM^3$/d) dissolves. The last difference with AHPD is in the inputs towards the reactor. The electricity consumption decreases because the pressure in the reactor lowers from 20 to 8 bar, which results in lower electricity consumption of the pumps. The heat demand lowers in the reactor because 10% of the injected hydrogen is used for biological processes producing heat (de Fooij & Hofstede, 2019). The calculation for the sludge flows can be found in Appendix 3.3. The calculations for the transportation can be found in Appendix 3.4. The calculations for the usage of heat and electricity can be found in

Appendix 4.1.3 and 4.2.3. Lastly, the calculations for the biomethane and surplus gas production and NG and hydrogen usage can be found in appendix 4.3.2.

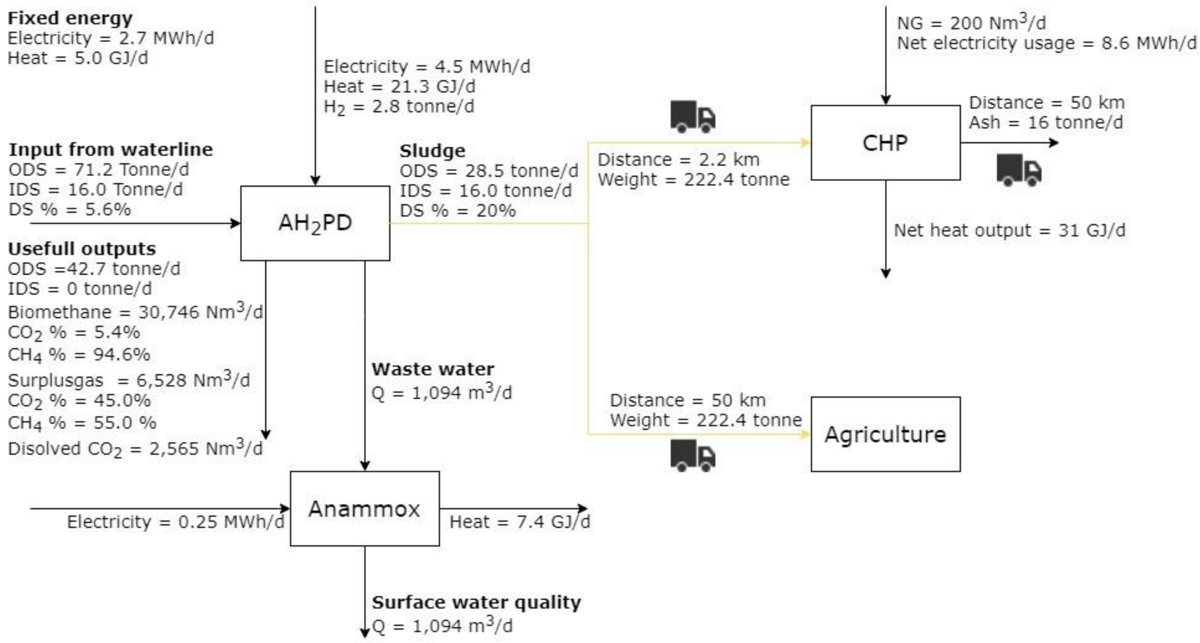


**FIGURE 20: MASS AND ENERGY FLOWS OF THE SLUDGE LINE WITH $AH_2PD$**

## 5.3.3 Flowcharts for the biogas line

Figure 21 shows the biogas flow for the gas produces in the baseline scenario. This flowchart is also used for the A-trap scenario. However, the biogas production is higher in the A-trap scenario. This difference is dealt with in the allocation section.

Part of the biogas is burned in a CHP and part of the biogas is burned in a torch. The electricity and heat production of the CHP are shown in the figure and based on measurements. The measurement for the electricity production is checked by a calculation in Appendix 4.1.1. This produced similar results.

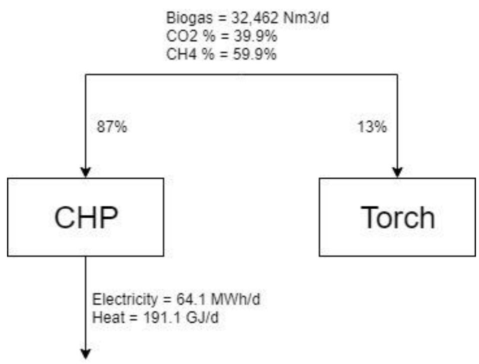


**FIGURE 21: BIOMETHANE USAGE AD**

$AH_{(x)}PD$ produces both biomethane and surplus gas. The biomethane is injected into the gas grid where it replaces NG. Figure 22 shows the surplus gas flow for the AHPD scenario. The surplus gas is burned in a boiler with an assumed LHV efficiency of 90%. This produces 89 GJ of heat per day for the AHPD scenario. For the $AH_2PD$ scenario, more surplus gas is produced with a higher methane concentration. This results in a heat production of 115 GJ/d. Both calculations can be found in appendix 4.1.3.

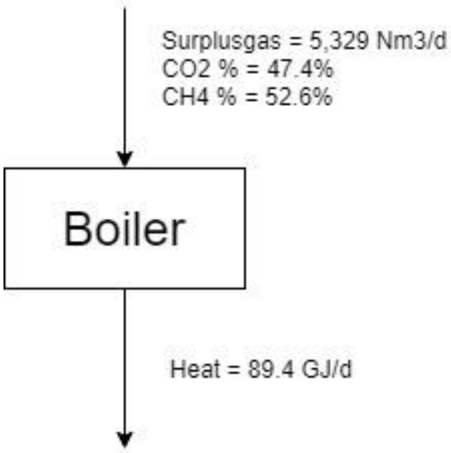


**FIGURE 22: SURPLUS GAS USAGE AHPD**

## 5.4 Mass allocation of the internal sludge input.

Allocation of the mass and energy flows is needed to filter out the external sludge input from other waterboards to the AD as explained in the method (section 4.1.3). The allocation takes place based on COD flows. The internal share of the COD input is equal for the PST, AT and ST in the waterline and is equal for the AD, the centrifuge and the processes after the centrifuge (CHP) in the sludge line.

### 5.4.1 Allocation for the baseline scenario

External sludge of other waterboards is also converted in the AD of the WWTP Amsterdam west. This increases the COD outflow in the digestate of AD which enters the centrifuge. The return flow from this centrifuge goes back towards the WWTP Amsterdam West where it increases the COD inflow to the wastewater treatment plant. Part of the return flow can be allocated to other waterboards, which decreases the COD input of Amsterdam West only. Figure 23 shows the external COD input and the return flow of the WWTP in Amsterdam west.

Based on measurements, the return flow to the waterline should be 17.7 tonne/d (Waternet, 2015). This return flow comes from the centrifuge, the gravitational thickener (located after the PST) and the mechanical thickener (located after the ST). However, to simplify the allocation this research assumes that the entire return flow of 17.7 tonne COD per day comes from the centrifuge. The calculations showed that the COD removal of the centrifuge equals 16.4 tonne per day, leaving 1.3 tonne COD per day to come from the gravitational thickener and the mechanical thickener.

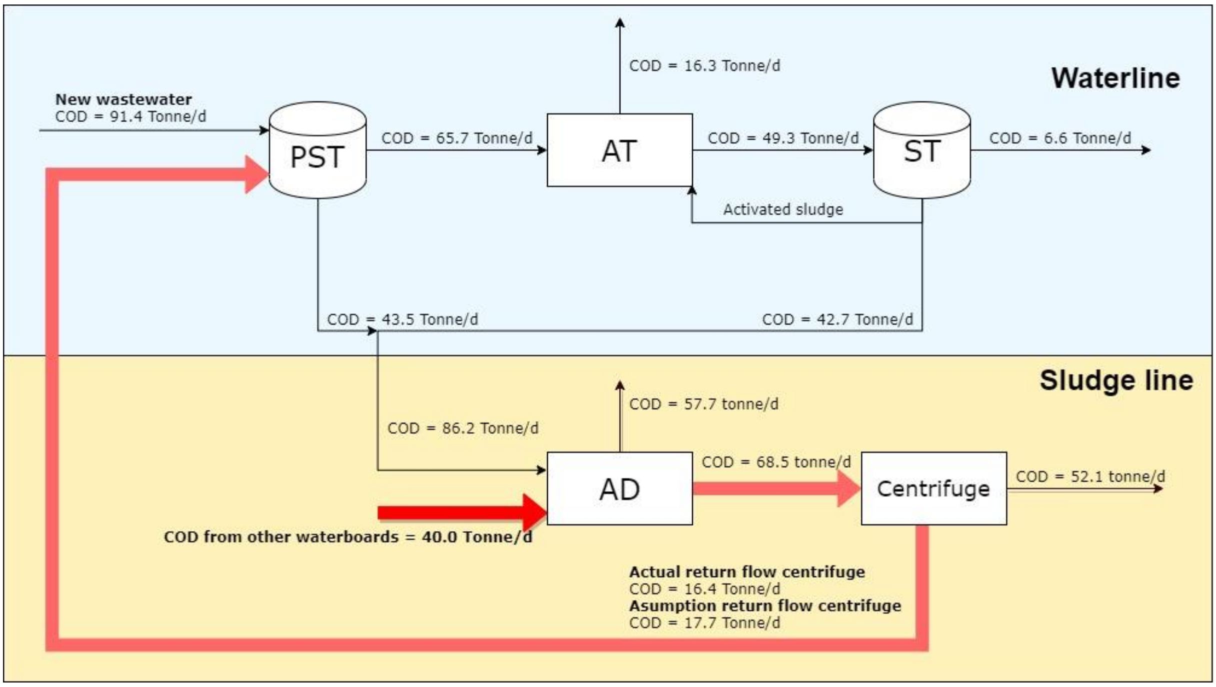


FIGURE 23: COD ALLOCATION OF THE RETURN FLOW OF THE EXTERNAL INPUT TOWARDS AD

All calculated COD flows, as displayed in Figure 23, include the external COD input from other waterboards that enter the AD. To isolate this external COD flow from other waterboards iteration is used, for the water- and sludge line. This iteration process is visualised in Figure 24. The most important calculations providing the results of this Figure can be found in Appendix 5.1.

The iteration is started with the assumption that the entire COD input from the waterline to the AD of 86,2 tonne COD is internal. However, this is not the case as explained above. The COD in the return flow from the centrifuge is at the start of the iteration for 68.3% internal (86.2/(40+86.2)), resulting in an internal COD flow in the waterline of 94.9% ((0,683*17.7+91.4)/(17.7+91.4)). The first iteration (Loop 1) calculates the internal share (blue bar) and external share (orange bar) of the COD input from the waterline to the AD. Because part of the COD input from the waterline to AD is external in the first loop, the internal allocation factor for the water- and sludge line decreases. The internal COD flow in the sludge line and the internal COD flow in the waterline are iterated until the external share of the COD input from the waterline to the AD remained constant at 3 decimals. The iteration results in an internal COD flow in the sludge line of **64.4%** and an internal COD return flow in the waterline of **94.2%**.

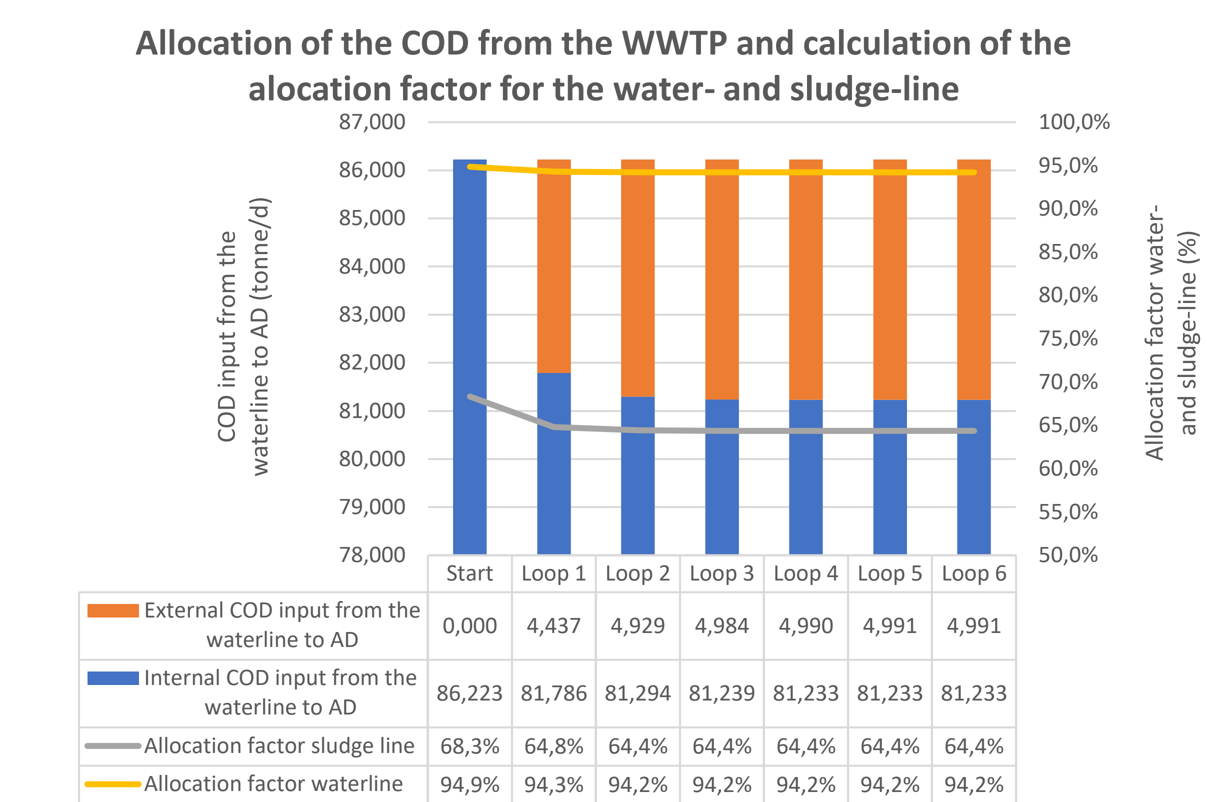


**FIGURE 24: COD ALLOCATION FOR THE BASELINE SCENARIO**

### 5.4.2 Allocation for the A-trap scenario

In case an A-trap is installed instead of a PST, the iteration method remains the same, but the results of the allocation change. When an A-trap is installed, the return flow from the centrifuge will change as well because of the increased COD input to the AD from the waterline. The new return flow from the centrifuge is iterated in Appendix 5.2. This resulted in a return flow from the centrifuge towards the waterline of 19.8 tonne COD per day.

The method of calculating the allocation factor for the sludge and waterline is the same as for the baseline scenario. The results of the iteration in the A-trap scenario can be found in Table 7. The internal COD input from the waterline to AD remained constant after the fifth loop. This resulted in the allocation factor for the sludge line of **67.5%** and an allocation factor of the waterline of **94.2%**

**TABLE 7: COD ALLOCATION FOR THE A-TRAP SCENARIO**

| | Internal COD input from the waterline to AD (Tonne/d) | External COD input from the waterline to AD (Tonne/d) | Allocation factor sludge line | Allocation factor waterline |
|---|---|---|---|---|
| **Start** | 101,139 | 0,000 | 71,672% | 94,951% |
| **Loop 1** | 96,032 | 5,106 | 68,053% | 94,306% |
| **Loop 2** | 95,380 | 5,758 | 67,591% | 94,224% |
| **Loop 3** | 95,297 | 5,842 | 67,532% | 94,213% |
| **Loop 4** | 95,286 | 5,852 | 67,525% | 94,212% |
| **Loop 5** | 95,285 | 5,854 | 67,524% | 94,212% |
| **Loop 6** | 95,285 | 5,854 | 67,524% | 94,212% |

The A-trap scenario needs, in contrast to the baseline scenario, separate allocation for the biogas line as well. For the A-trap scenario, the share of primary sludge compared to surplus sludge changes, which results in a higher biogas production per sludge input. Also, the total sludge production increases. As explained in section 5.1, primary sludge produces 1100 Nm3 biogas per tonne ODS removed and surplus sludge produces 700 Nm3 biogas per tonne ODS removed. Both productions are multiplied by 0.89 (See appendix 1.1) to make the biogas production based on literature match the actual production.

The biogas production in the A-trap scenario is calculated in Formula 13. As calculated earlier, 94.2% of the COD from the waterline in the A-trap scenario can be allocated to Amsterdam West. Formula 14 calculates the correct allocation factor for the biogas line, which is calculated by dividing the new biogas production by the total biogas production of the WWTP Amsterdam West.

$$[\mathbf{13}]: Biogas\ production\ A - trap\ scenario$$
$$= \frac{82.3\ \left(\frac{Tonne\ primary\ COD}{d}\right) * 0{,}942\ (Alocation\ \ waterline\ A - trap)}{1.42\ \left(\frac{Tonne\ COD}{Tonne\ ODS}\right)} * 1100\ \left(\frac{Nm3}{Tonne\ primary\ ODS}\right) * 0{,}89\ (Correction\ factor)$$
$$+ \frac{18.9\ \left(\frac{Tonne\ surplus\ COD}{d}\right) * 0{,}942\ (Alocation\ \ waterline\ A - trap)}{1.42\ \left(\frac{Tonne\ COD}{Tonne\ ODS}\right)} * 700\left(\frac{Nm3}{Tonne\ surplus\ ODS}\right) * 0{,}89\ (Correction\ factor) = 27{,}877\frac{Nm3}{d}$$

$$[\mathbf{14}]: Allocation\ factor\ biogas\ production\ A - trap$$
$$= \frac{Total\ biogas\ production\ A - trap}{Total\ biogas\ production\ WWTP\ AW\ (Waternet\ AW, 2015)} * 100$$
$$= \frac{27{,}877\ \left(\frac{Nm3}{d}\right)}{32{,}462\ \left(\frac{Nm3}{d}\right)} * 100 = \mathbf{85.9}\%$$

## 5.4.3 Allocation for the AHPD and AH$_2$PD scenario

For the AH$_{(x)}$PD scenarios, less allocation is needed. This is because the mass and energy flows of AHPD and AH$_2$PD are calculated based on the COD input to AHPD from the waterline. The COD input to AHPD changes because of a changing return flow, which is calculated underneath

Measurements of the COD return flow in the test reactor of Bareau (2020) indicated a return flow of 120 mg COD per litre. The water output of the AH$_{(x)}$PD reactor is approximately the same as that of the centrifuge in the A-trap scenario since the DS% of the sludge is approximately the same and therefore the same amount of water needs to be rejected. The return flow for AH$_{(x)}$PD is calculated in Formula 15.

$$[\mathbf{15}]: COD\ return\ flow\ AH(x)PD = COD\ in\ return\ flow * Volume\ of\ the\ return\ flow$$
$$= 120\left(\frac{mg}{l}\right) * 1915\ \left(\frac{m3}{d}\right) * 1000\ \left(\frac{l}{m3}\right) = 230 * 10^6\frac{mg}{d} = 0.230\ (\frac{tonne}{d})$$

The COD in the new wastewater in Amsterdam west is 91.4 tonne/d. This means that the return flow contributes less than 1% to the COD input of the WWTP Amsterdam West and can, therefore, be excluded from this research. This simplifies the allocation. The allocation factor for AH$_{(x)}$PD is calculated in Formula 16 and can be used for the water, sludge and biogas line.

$$[\mathbf{16}]: Allocation\ factor\ AH(x)PD = \frac{New\ COD\ in\ wastewater\ to\ the\ waterline}{New\ COD\ in\ wastewater\ to\ the\ waterline + Old\ COD\ return\ flow\ in\ the\ baseline\ scenario} * 100 = \frac{91.4\ \left(\frac{tonne}{d}\right)}{91.4\ \left(\frac{tonne}{d}\right) + 19.8\ \left(\frac{tonne}{d}\right)} * 100 = \mathbf{82.2}\%$$

### 5.4.4 Summary results allocation.

The results of the allocation are summarised in Table 8. For the baseline scenario, the allocation factor for the sludge- and biogas- line is the same. This is because there are no external inputs in the biogas line, and no processes changes in the biogas line. There are no different allocation factors for the sludge- and biogas-line for the $AH_{(x)}PD$ scenarios. Since the sludge input from the waterline is partly external, the sludge- and biogas line should be allocated as well with the same allocation factor.

**TABLE 8: SUMMARY RESULTS ALLOCATION**

| | Waterline | Sludge line | Biogas line |
|---|---|---|---|
| Allocation factor baseline scenario | **94.2 %** | **64.4 %** | **64.4 %** |
| Allocation factor A-trap scenario | **94.2 %** | **67.5 %** | **85.9 %** |
| Allocation factor for the $AH_{(x)}PD$ scenarios | **82.2 %** | **82.2 %** | **82.2 %** |

# 6. Results

The greenhouse gas emissions of the four different scenarios are given in this section. All emissions are noted per year and valid for the WWTP Amsterdam West. The calculations are based on the results of sections 5.2, 5.3 and 5.4. The basic formula to calculate the results is explained in the methodology in section 4.3. All results include biogenic $CO_2$ emissions. The scale of the biogenic $CO_2$ emissions for all scenarios is quantified in section 6.5, where the total emissions are divided into biogenic $CO_2$, fossil $CO_2$, $CH_4$ and $N_2O$. The last part of the results (section 6.6) indicates the GWP of treating the wastewater of only Gaasperdam.

## 6.1 Results baseline scenario

The results for the baseline scenario are given in Figure 25. The major contributors to the total GWP are the usage of the biogas from the AD, the biological COD removal and the $CH_4$ leakage from the sludge line. About 87% of the biogas is used in a CHP plant, which produces almost all electricity needed for the WWTP and a surplus of heat, which is however not given any credit, as there is no local use for the available heat. The rest of the biogas is burned in a torch. The biological COD removal comes from the oxidation of the sludge, the CHP at AEB which burns the digested sludge and the COD which is released to surface water. The $CH_4$ leakage from the sludge line is due to the sludge thickeners and buffers. The NG usage is little and due to the heat requirements at AEB to evaporate the water and burn the digested sludge. The $N_2O$ emissions from the waterline contribute marginal to the GWP, however since the emission factor is very uncertain, this parameter can potentially increase. Lastly, the transport of the sludge to the CHP at AEB and the transport of the ash from AEB have a small contribution to the GWP. This is mainly because the wet sludge is transported for only 2.2 km to the CHP at AEB.

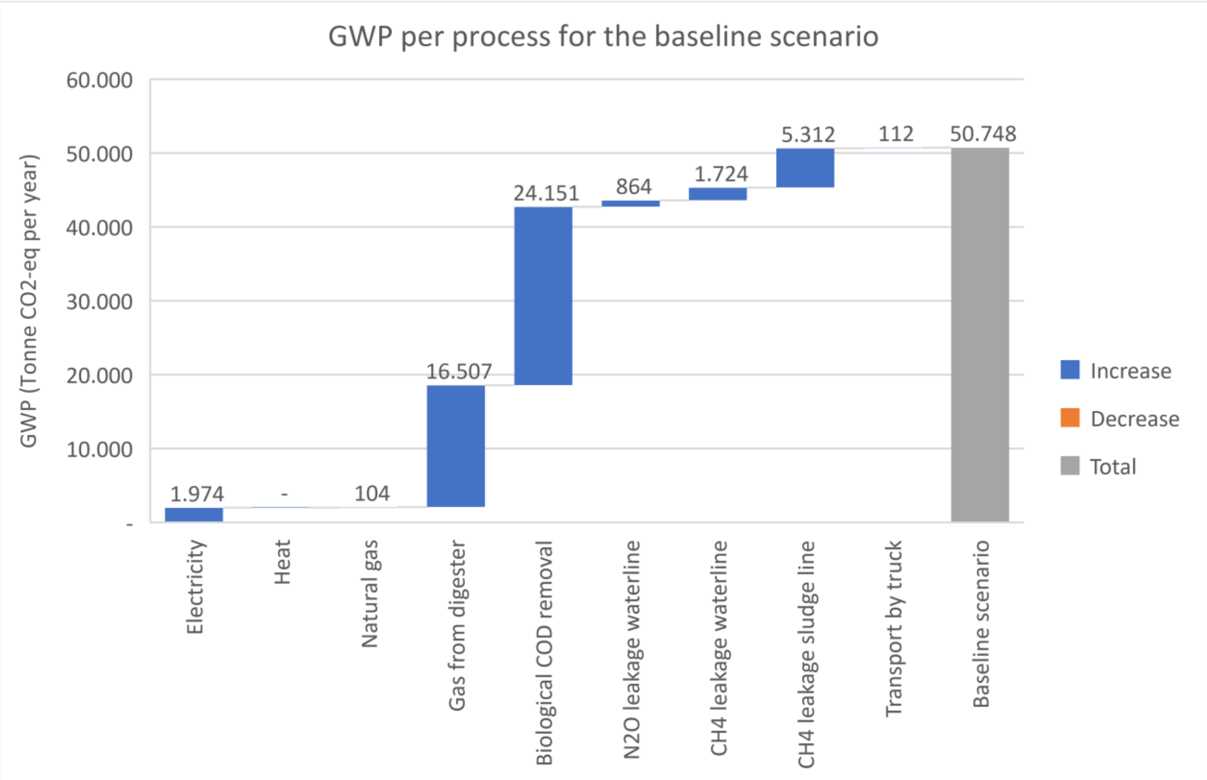


**FIGURE 25: GWP PER PROCESS BASELINE SCENARIO**

## 6.2 Results A-trap scenario

Figure 26 shows the difference in GWP per process when the baseline scenario changes towards the A-trap scenario. Installing an A-trap reduces the total yearly GWP by 4*$10^3$ tonne $CO_2$-eq per year. The major contributors to the increase in GWP are the biogas usage from the AD and the $CH_4$ leakage in the sludge line. The A-trap scenario produces more sludge of which a higher percentage is primary sludge. Both reasons increase the biogas production (gas from digester), leading to an increase in GHG emissions from the torch and CHP. The $CH_4$ emissions in the sludge line increase because more sludge is treated in the sludge line. The major contributors to a decrease in GWP are the electricity usage, the biological COD removal and the $CH_4$ leakage in the waterline. The increasing the biogas input of the CHP increases the electricity and heat production. This leads to a reduction in GHG emissions from electricity usage. The additional heat production is not credited because there was already an overproduction. The GHG emissions of the biological removed COD decrease because the increasing biogas production causes a reduction in carbon which remains in the sludge. The $CH_4$ emissions in the waterline decrease because less COD is oxidised in the AT and less COD remains in the effluent. Lastly, the GHG emissions of NG usage and transportation increase slightly. This is because more sludge is burned at AEB (increasing NG consumption) and more sludge and ash is transported because of the increased sludge production.

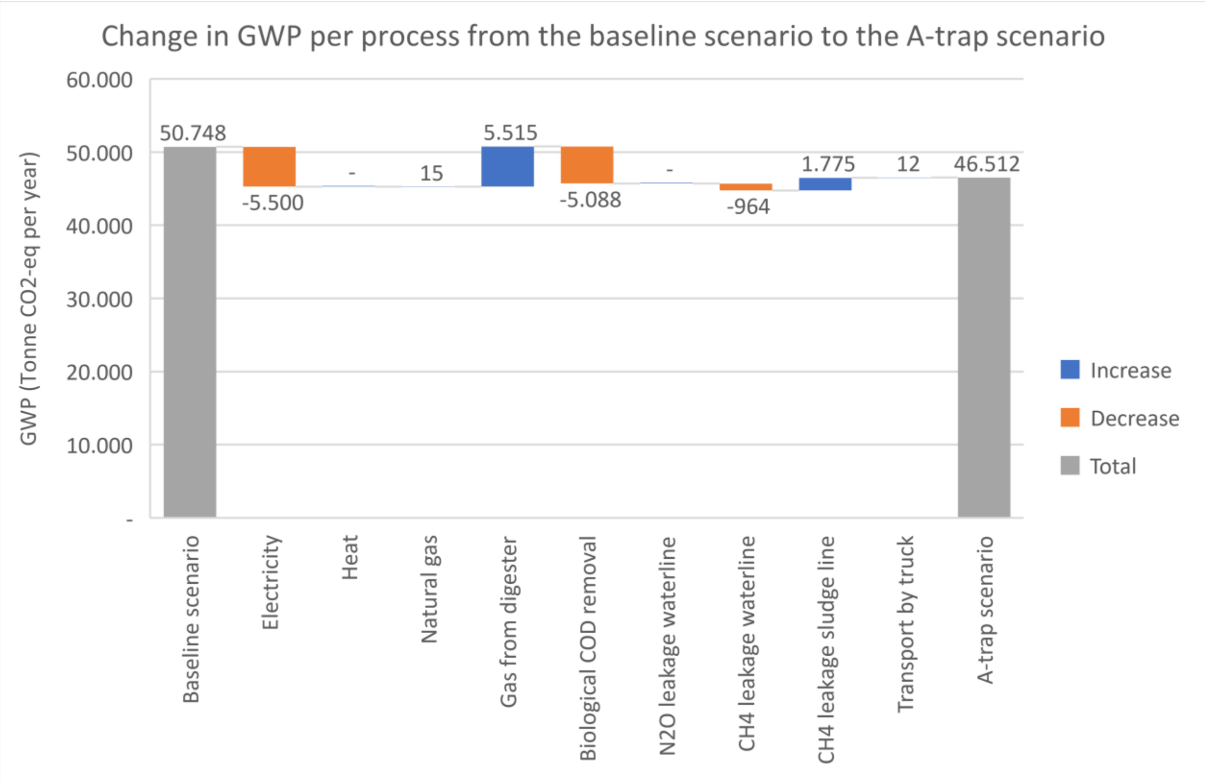


**FIGURE 26: CHANGE IN GWP PER PROCESS FOR THE A-TRAP SCENARIO**

## 6.3 Results AHPD scenario

The change in GWP from the baseline to the AHPD scenario is shown in Figure 27. The end-use of the digested sludge in this figure is at the CHP at AEB. Installing an A-trap in combination with AHPD reduces the total GWP with $14*10^3$ tonne $CO_2$-eq per year. The major contributors to the increase in GWP are the electricity usage and the dissolved $CO_2$. No electricity is produced anymore in this scenario, resulting in the need for electricity from the grid. The dissolved CO2 is a new parameter and is a consequence of the reactor pressure of AHPD. This CO2 is released into the environment when the pressure drops. One additional minor increase in GWP is caused by the increased gas production from the digester. The biogenic GHG emissions of burning the surplus gas and biomethane are more than the emissions of burning the biogas during AD. The end-use of the biomethane is included since the reduction in GWP by the biomethane is already included in the substitution of natural gas, and GHG emission reductions would otherwise be counted double. The major contributors to the decrease in GWP are the NG substitution by the biomethane production and the biological COD removal. The minor NG usage of AEB changes into a substantial biomethane production that is injected in the grid. The GWP of the biological COD removal decreases because of two different reasons. The first reason is that the increased sludge input from the A-trap and the increasing share of primary sludge increases the biogas production. The second reason is that an AHPD installation converts more of the sludge towards gas than an AD installation. This is caused by the longer sludge retention time and the higher temperature within the reactor. Two additional minor reductions in the GWP are caused by the reduced $CH_4$ leakage in the water- and sludge line. Less $CH_4$ is leaked in the waterline because of the decrease in COD which is oxidised in the AT and released towards the surface water. The $CH_4$ emissions in the sludge line decrease because an AHPD consists of one settler, whereas an AD has two. The second settler is integrated into the AHPD reactor. Therefore, the $CH_4$ which would have leaked into the environment during AD is now turned into useful gas. Lastly, the GHG emissions of transportation slightly increase because of the increase in sludge production of an A-trap and the increased water content of the sludge (20% DS instead of 22% DS).

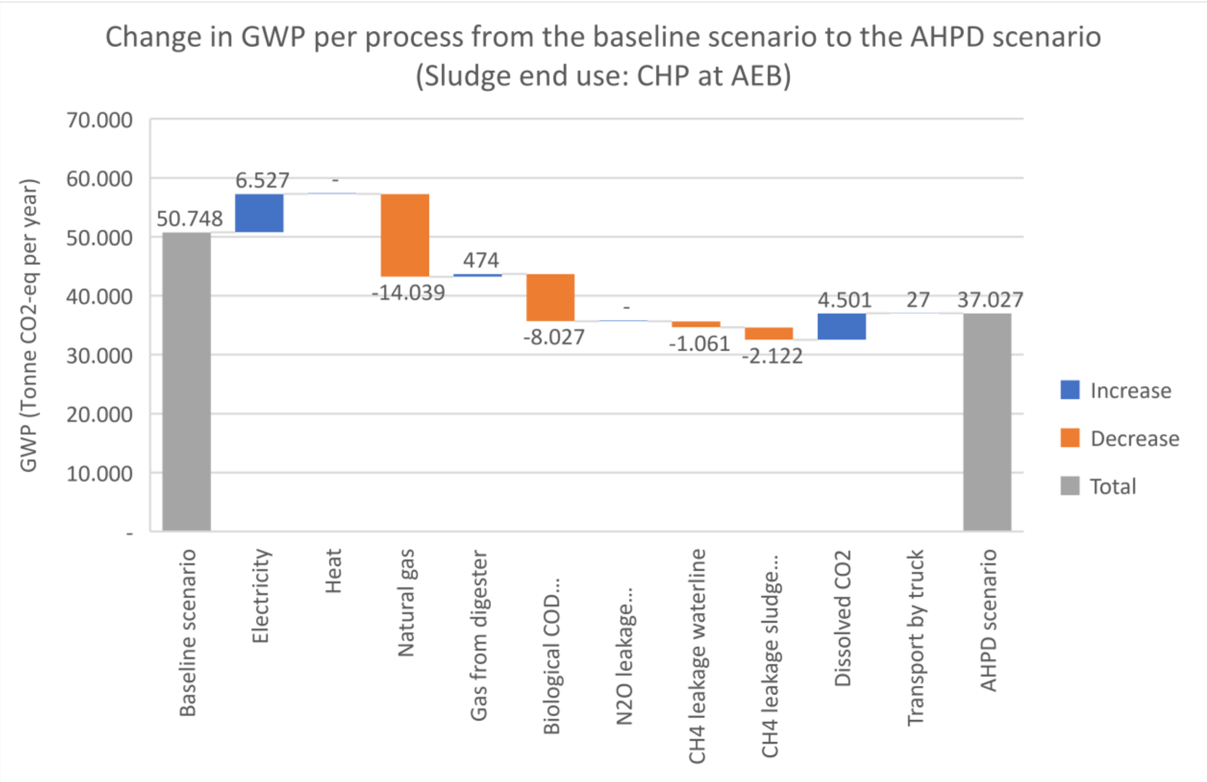

FIGURE 27: CHANGE IN GWP PER PROCESS FOR THE AHPD SCENARIO (SLUDGE END-USE: CHP AT AEB)

The change in GWP from the baseline to the AHPD scenario with the end-use of the sludge as a fertiliser is shown in Figure 28. The total GWP reduction potential is $19*10^3$ tonne $CO_2$-eq per year. Only the differences which are caused by the different end-use are explained here. The processes which are influenced by the different end-use are electricity, NG, transportation, and fertiliser production. The CHP at AEB consumes NG and had a net electricity consumption. Changing the end-use removes the need for this electricity and NG and therefore reduces the GWP. The GHG emissions of the transportation increases because the wet sludge (20% DS) is transported for 50 km to be used as a fertiliser instead of 2.2 km to the CHP of AEB. Lastly, the usage of digested sludge as a fertiliser substitutes the need for other fertilisers which is credited with a negative GWP.

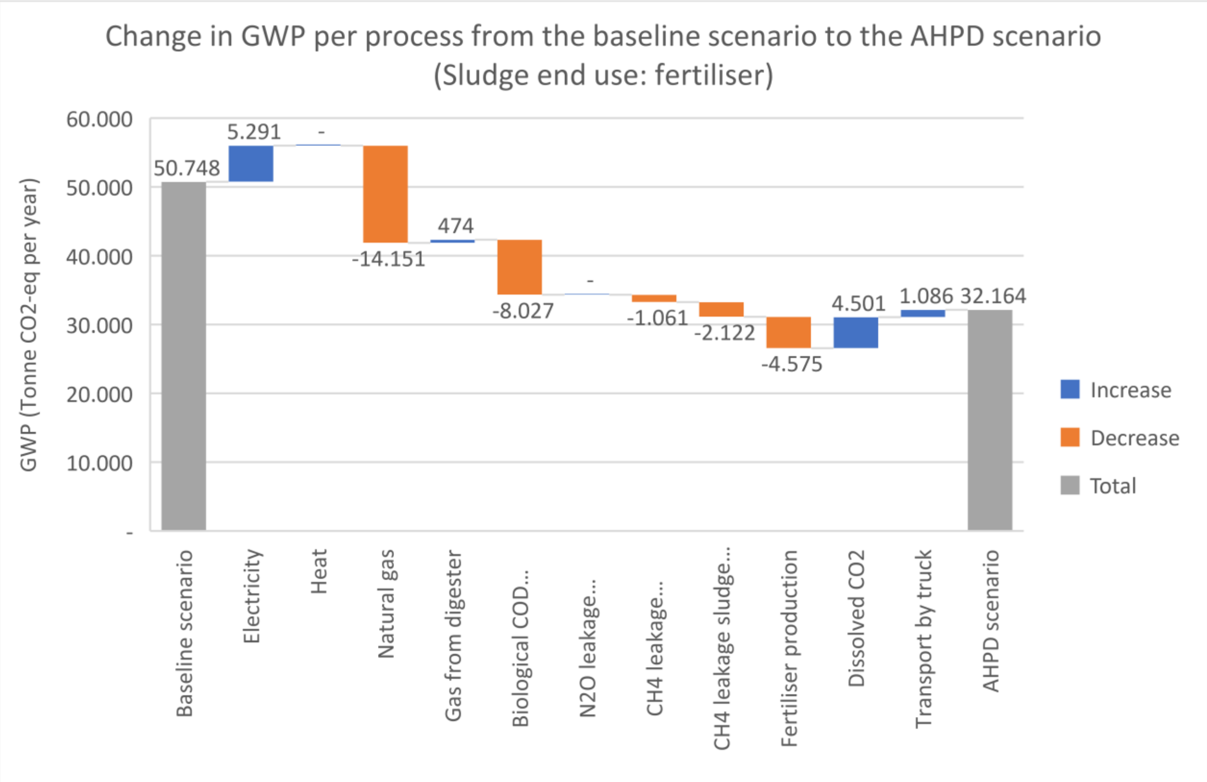


FIGURE 28: CHANGE IN GWP PER PROCESS FOR THE AHPD SCENARIO (SLUDGE END-USE: FERTILISER)

## 6.4 Results $AH_2PD$ scenario

The change in GWP from the baseline scenario to the $AH_2PD$ scenario is shown in Figure 29. The end-use of the digested sludge in this figure is at the CHP at AEB. This scenario reduces the total GWP by $14*10^3$ tonne $CO_2$-eq per year. The underlying principles of the change per process for AHPD are the same as for $AH_2PD$ in case of the same end-use for the digested sludge. This section highlights the differences in the change in GWP between AHPD and $AH_2PD$. The first difference is that more biomethane and surplus gas is produced by the injection of $H_2$. The increase in biomethane production leads to a reduction in fossil GHG emissions of the substituted fossil NG, but also to an increase in biogenic GHG emissions of the biomethane (gas from the digester). The increased amount of surplus gas (gas from the digester) is burned in a boiler leading to an additional increase in GHG emissions. The injected $H_2$ is produced using PV electrolysis causes $2.6*10^3$ tonne $CO_2$-eq emissions per year. The injected hydrogen allows reducing the pressure in the AHPD reactor without compromising the methane concentration of the gas since part of the dissolved $CO_2$ reacts with the $H_2$ to form $CH_4$. The pressure drop in the reactor decreases the electricity demand for the pumps and therefore decreases the GHG emissions of the electricity usage. Lastly, the GHG reduction of dissolved $CO_2$ can be explained by the conversion of $CO_2$ into $CH_4$ because of the $H_2$ injection.

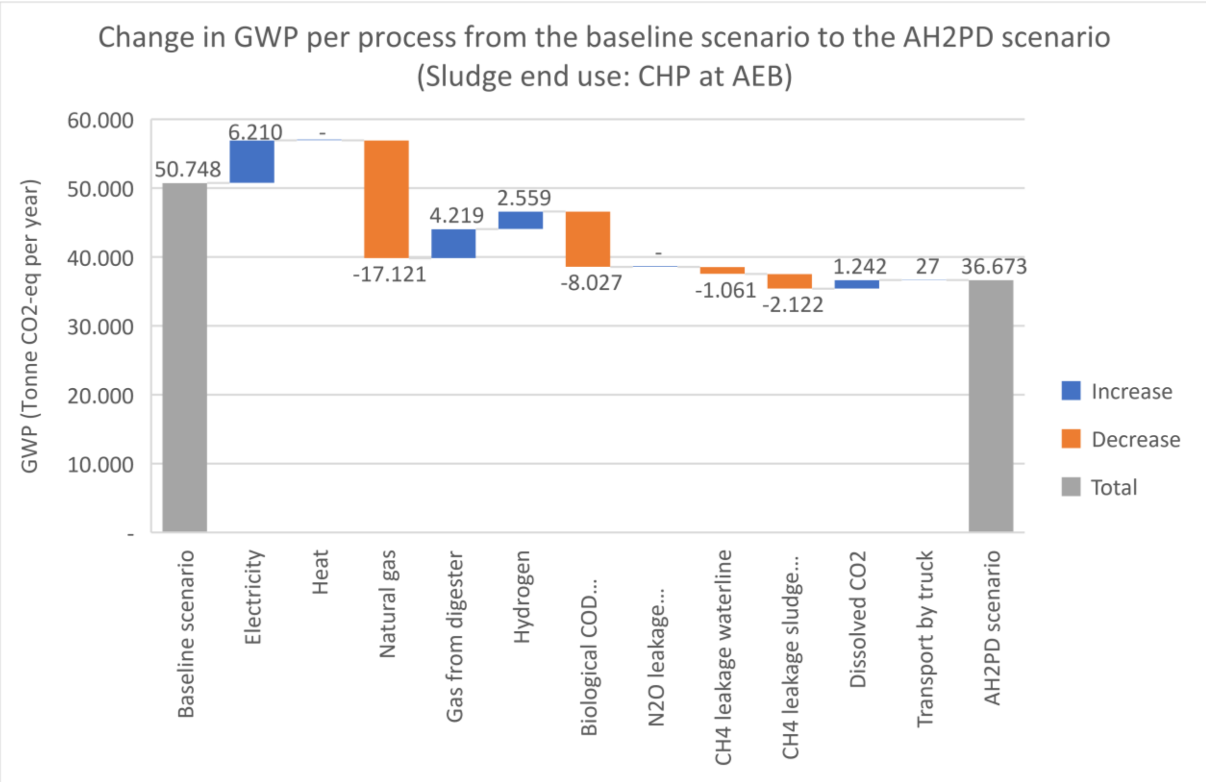


**FIGURE 29: CHANGE IN GWP PER PROCESS FOR THE $AH_2PD$ SCENARIO (SLUDGE END-USE: CHP AT AEB)**

Figure 30 shows the change in GWP from the baseline scenario to the $AH_2PD$ scenario for the end-use of the sludge as a fertiliser. The total GWP decreases by $19*10^3$ tonne $CO_2$-eq per year for this scenario. The difference in GWP between the CHP end-use and the fertiliser end-use is the same for the $AH_2PD$ scenario as for the AHPD scenario. The underlying principles of this difference are also equal and can be found in section 6.3 under the fertiliser scenario.

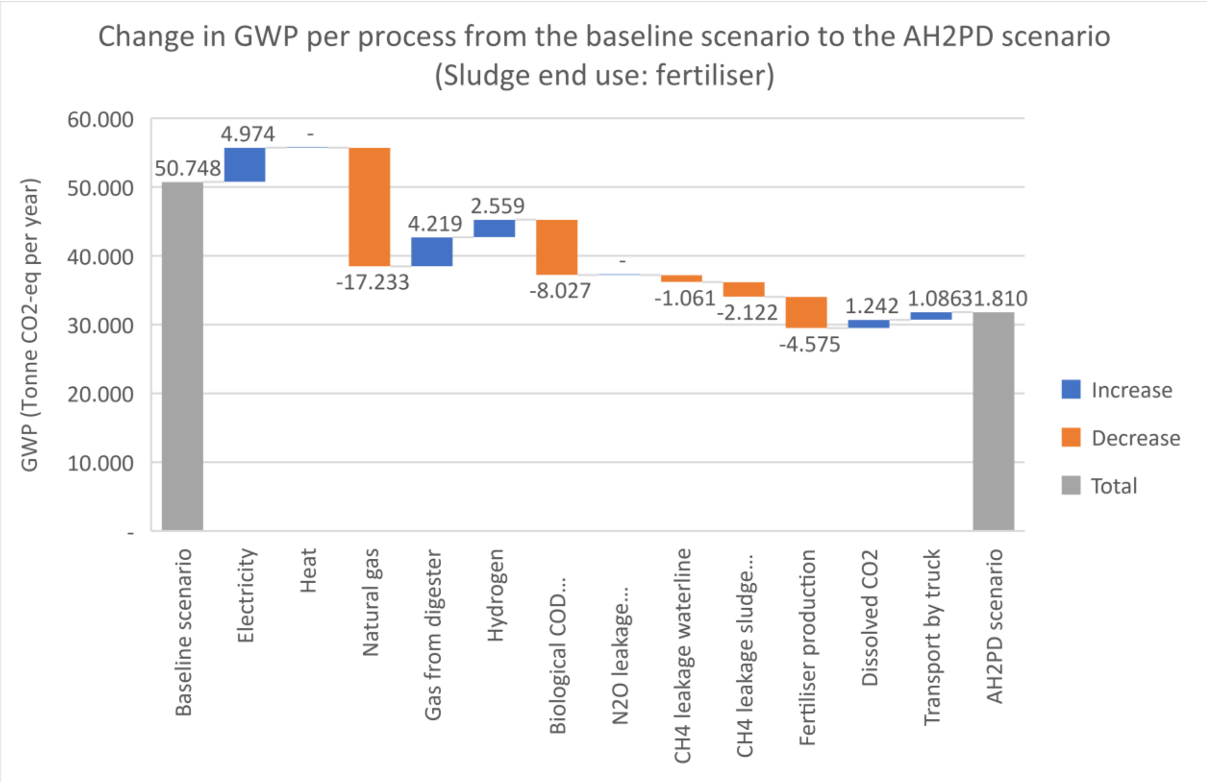


**FIGURE 30: CHANGE IN GWP PER PROCESS FOR THE $AH_2PD$ SCENARIO (SLUDGE END-USE: FERTILISER)**

## 6.5 Summary results

The GWP of the four different scenarios (including two different types of end-use of the digested sludge from AHPD or $AH_2PD$) is shown in Figure 31. This figure divides the total emissions per scenario into biogenic CO2, fossil $CO_2$, $CH_4$, and $N_2O$. All scenarios reduce the GWP of the baseline scenario, however, the $AH_{(x)}PD$ scenarios reduce the GWP more than the A-trap scenario. As can be seen from this figure, the $AH_2PD$ scenario with the end-use of the sludge as a fertiliser performs best. However, the difference between the GWP of the AHPD and $AH_2PD$ scenario with the same end-use is small. This is caused by the emissions of hydrogen production, which compensate for the emission reduction of the additional biomethane production.

Figure 31 shows that all scenarios emit approximately $38*10^3$ tonne biogenic $CO_2$ per year. However, the scenarios differ from each other in the biogenic $CO_2$ which is emitted due to the combustion of biologically produced methane in energy-producing processes. The baseline scenario emits 29% of its biogenic $CO_2$ because of the methane in the biogas which is burned in the CHP. For the A-trap scenario, this share is 38%. For the $AH_{(x)}PD$ scenario's, between 55% and 64% of the biogenic $CO_2$ emissions are emitted because of the end-use of the methane in the biogas and surplus gas for energy production.

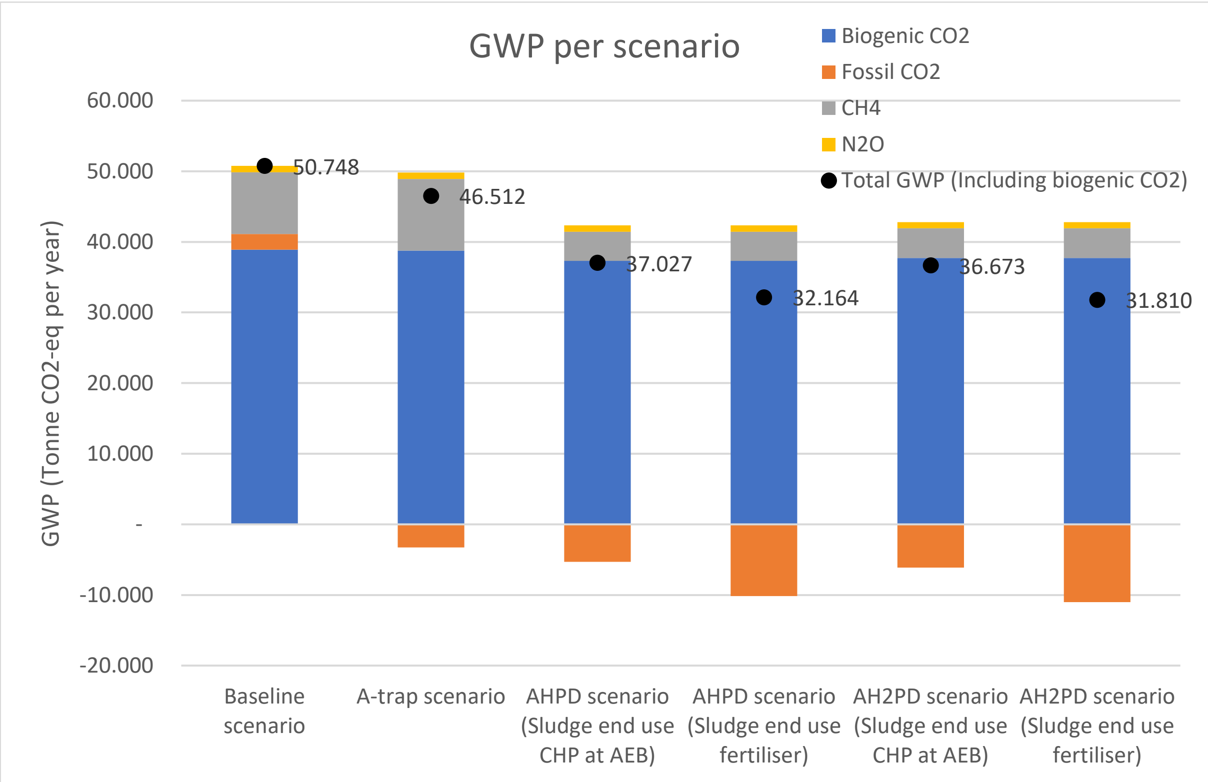


**FIGURE 31: SUMMARY GWP PER SCENARIO**

## 6.6 Results of the case study

It is difficult to define the GWP for Gaasperdam based on the GWP of the WWTP Amsterdam West. Gaasperdam treats $33*10^3$ PE's per year, where the WWTP Amsterdam West treats $906*10^3$ PE's per year. As explained in section 4.2 of the methodology, the GWP of Gaasperdam is scaled based on two different scaling factors (0.7 and 1.0). The GWP per scenario including biogenic $CO_2$ is shown in Figure 32. The GWP for all scenarios is 2.7 times higher for the exponential scaling factor of 0.7 as for the linear scaling factor of 1.0.

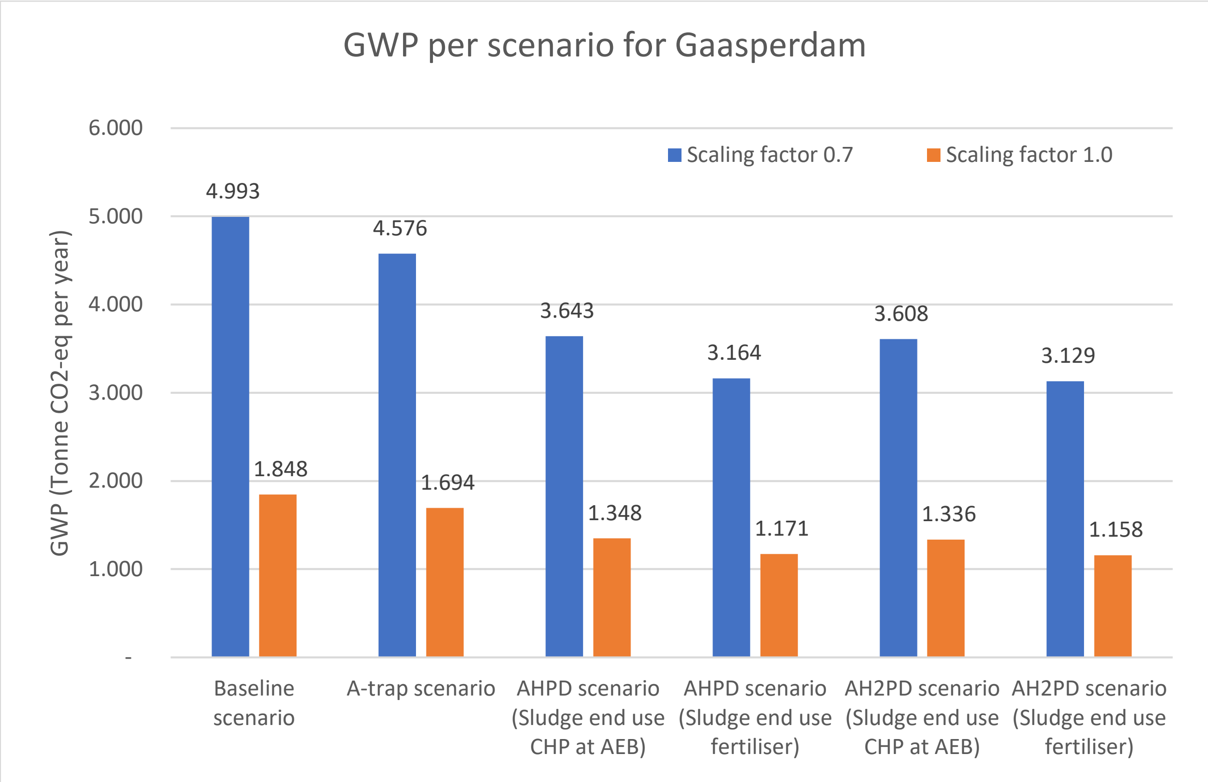


**FIGURE 32: GWP PER SCENARIO FOR GAASPERDAM**

# 7. Sensitivity analysis

Section 7.1 focusses on the uncertain input parameters. This section explains and visualises the impact of the uncertainty in the input parameters on the GWP using spider diagrams. Section 7.2 focusses on the effect of different modelling assumptions on the GWP. This section explains the difference in the results and discusses among others if the best performing scenario will change under a different modelling assumption.

## 7.1 Sensitivity analysis on uncertain input parameters

The sensitivity analysis is performed on six parameters; heat usage, electricity usage, transportation distance, COD removal efficiency A-trap, emission factor $H_2$ and the emission factor of $N_2O$. As explained in the methodology, these parameters were selected based on the degree that they can influence the result or contribute to the variance in the output. Other parameters, like the ODS removal percentage and the gas production per mass of ODS, are not ranged because it is assumed that they will not significantly influence the results. It is not possible to display the emission factor of $N_2O$ in a spider diagram because it would harm the visibility of the other parameters. The uncertainty in the emission factor of $N_2O$ is equal for all scenarios. Under normal circumstances, this uncertainty can increase the GWP from $1*10^3$ tonne $CO_2$-eq/year (current emission factor) towards $25*10^3$ tonne $CO_2$-eq/year (increase in $N_2O$ emission factor of 2857%). As explained in the sensitivity analysis, the $N_2O$ emissions can incidentally be up to 95% higher than the maximum value of the range under normal circumstances. This parameter influences the results the most. The effect of the other parameters is explained and visualised underneath for each scenario. All spider diagrams include biogenic $CO_2$.

### 7.1.1 Baseline scenario

The sensitivity analysis for the baseline scenario is shown in Figure 33. Noticeable is that the electricity usage has the largest influence on the GWP. The transportation distance only has a marginal influence on the GWP. The heat usage does not influence the GWP since the heat production is always more than the heat usage and the overproduction of heat is not credited with a negative GWP. Ranging one parameter at a time keeps the total GWP between $48*10^3$ and $53*10^3$ tonne $CO_2$-eq per year.

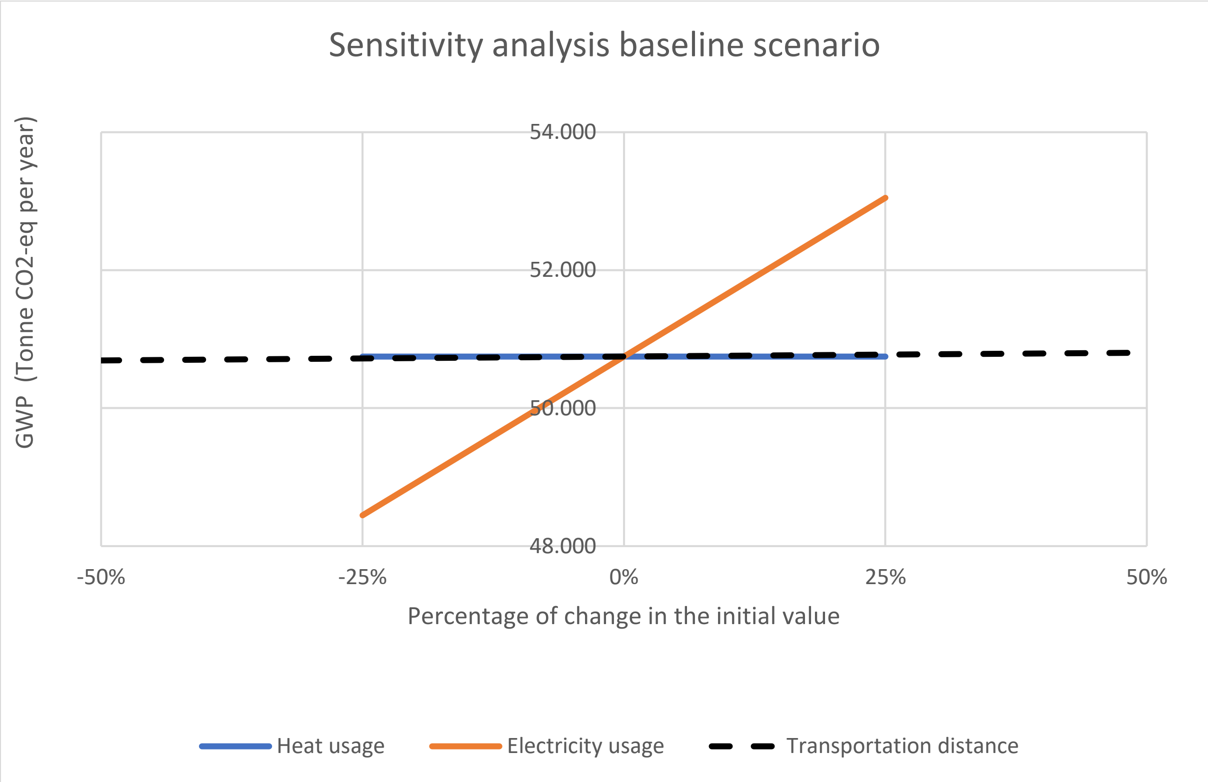


**FIGURE 33: SENSITIVITY ANALYSIS BASELINE SCENARIO**

### 7.1.2 A-trap scenario

The sensitivity analysis for the A-trap scenario is shown in Figure 34. The sensitivity in the electricity usage and the COD removal efficiency of the A-trap have influences the GWP the most. The transportation distance only has a marginal influence on the GWP. The heat usage does not influence the GWP since the heat production is always more than the heat usage. Ranging one parameter at a time keeps the total GWP between $43*10^3$ and $50*10^3$ tonne $CO_2$-eq per year.

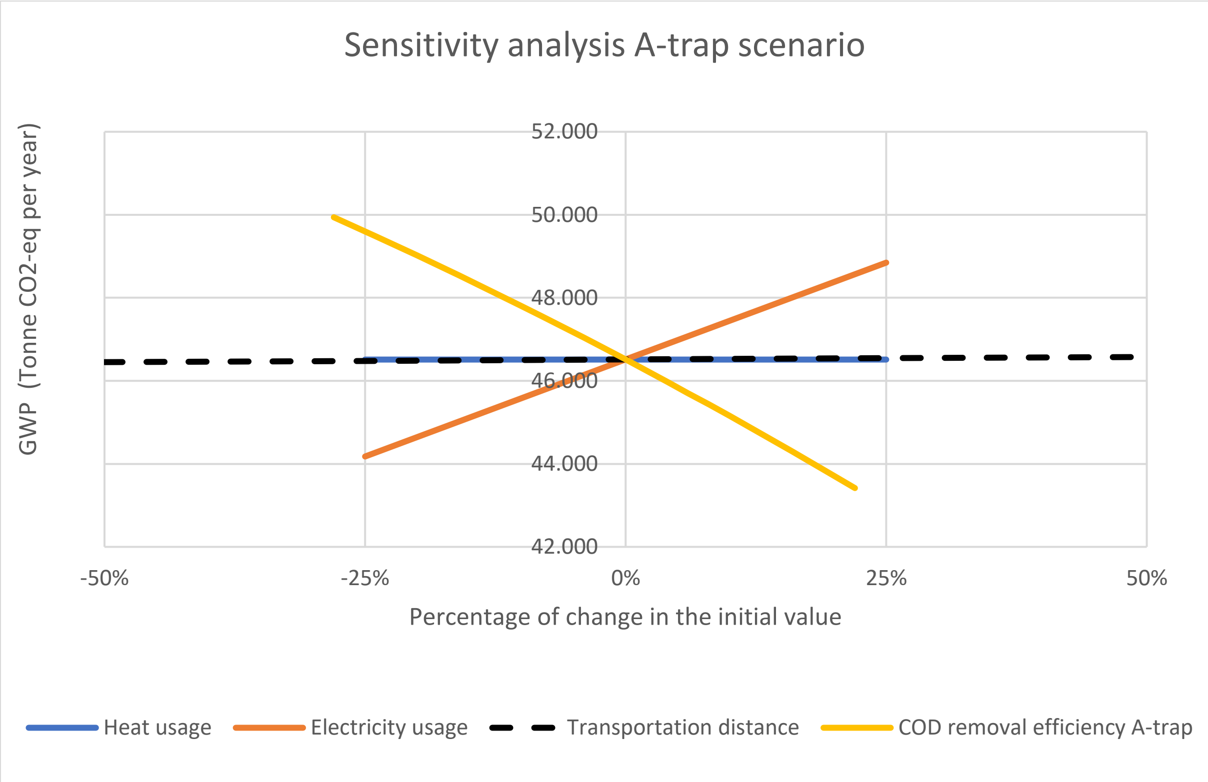


**FIGURE 34: SENSITIVITY ANALYSIS A-TRAP SCENARIO**

### 7.1.3 AHPD scenario

The sensitivity analysis for the AHPD scenario is given in Figure 35. Both end-use possibilities for the digested sludge are shown in this figure (At the left the CHP at AEB, at the right fertiliser). Noticeable is that the electricity usage and the COD removal efficiency of the A-trap influence the GWP the most for both end-use possibilities. For the end-use of the digested sludge at the CHP at AEB, the transportation distance and the heat usage only have a marginal influence on the GWP. The impact of the transportation distance is low because the wet sludge (20% ds) is only transported for 2.2 km. The heat usage only influences the GWP at an increase of more than 50%. From this point the heat usage is more than the production, leading to a demand for external heat. For the end-use of the digested sludge as a fertiliser, the transportation distance and the heat usage have a small influence on the GWP. This type of end-use is however more sensitive to a change in both parameters. The sensitivity in the transportation distance increases because the wet sludge (20% ds) is transported for 50 km instead of 2.2 km. The sensitivity in the heat usage increases since no heat is produced at the CHP at AEB anymore. If the heat demand increases by more than 25%, external heat is needed. Ranging one parameter at a time keeps the GWP between $35*10^3$ and $45*10^3$ tonne $CO_2$-eq per year for the sludge and-use at the CHP of AEB. For the sludge end-use as a fertiliser, ranging one parameter at a time keeps the GWP between $30*10^3$ and $39*10^3$ tonne $CO_2$-eq per year. For both types of end-use, it means that the sensitivity in one parameter cannot increase the GWP of the AHPD scenario to a value that is higher than the GWP of the baseline or A-trap scenario.

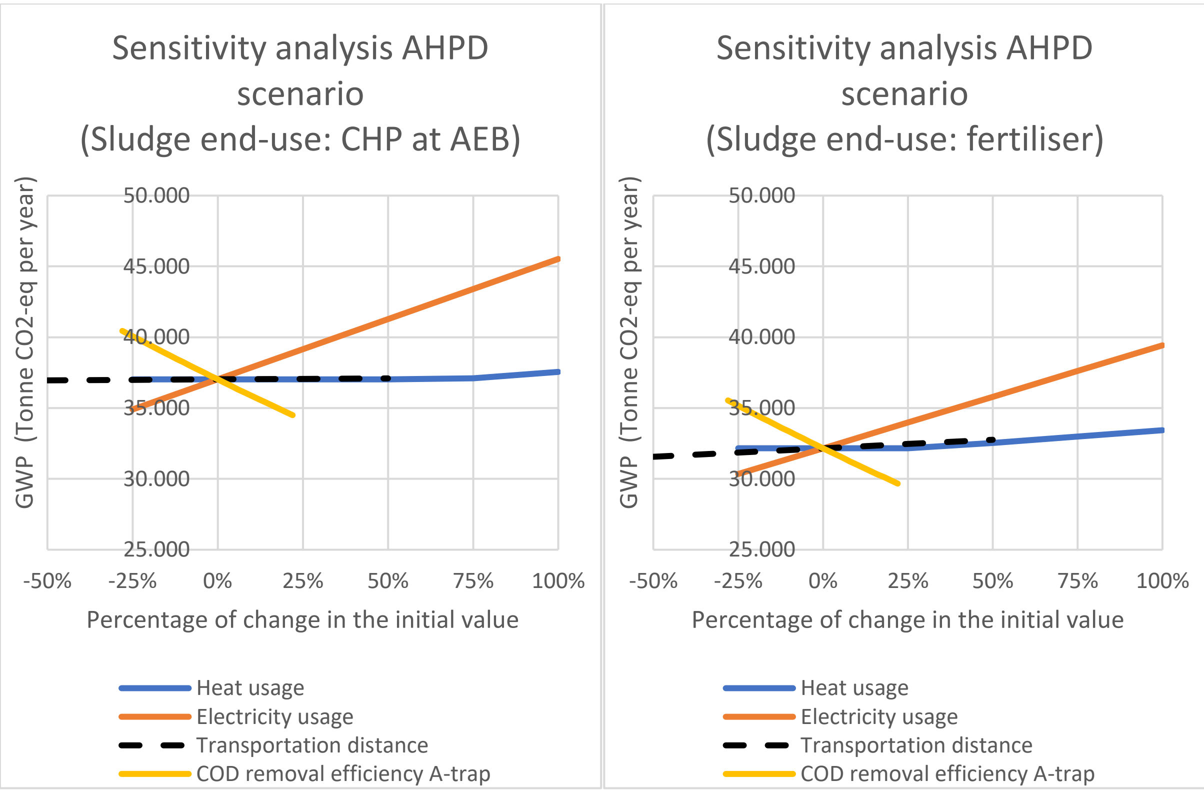


**FIGURE 35: SENSITIVITY ANALYSIS AHPD SCENARIO**

### 7.1.4 $AH_2PD$ scenario

The sensitivity analysis for the $AH_2PD$ scenario is visualised in Figure 36. Both end-use possibilities for the digested sludge are shown in this figure (At the left the CHP at AEB, at the right fertiliser). The GWP is influenced the most by the electricity usage, COD removal efficiency of the A-trap and the emission factor of $H_2$ for both end-use possibilities. Both figures show that the GWP of the $AH_2PD$ scenario is higher than that of the AHPD scenario if the emission factor for $H_2$ increases with approximately 25%. This means that the GWP of the $AH_2PD$ is only lower than that of AHPD if green hydrogen is used. For the end-use of the digested sludge at the CHP at AEB, the transportation distance has a marginal influence on the GWP, and the heat usage does not the GWP. The influence of the transportation distance is marginal since the wet digested sludge (20% ds) is only transported for 2.2 km. The heat usage does not influence the GWP since the heat production is always more than the heat usage. More heat is produced in this scenario than in the AHPD scenario since the reaction of $H_2$ and $CO_2$ towards $CH_4$ produces heat. For the end-use of the digested sludge as a fertiliser, the transportation distance and the heat usage have a small influence on the GWP. This type of end-use is however more sensitive to a change in both parameters, which is caused by the same reasons as explained in the AHPD scenario. Ranging one parameter at a time keeps the GWP between $34*10^3$ and $45*10^3$ tonne $CO_2$-eq per year for the sludge and-use at the CHP of AEB. For the sludge end-use as a fertiliser, ranging one parameter at a time keeps the GWP between $29*10^3$ and $39*10^3$ tonne $CO_2$-eq per year. For both types of end-use, it means that the sensitivity in one parameter cannot increase the GWP of the $AH_2PD$ scenario to a value which is higher than the GWP of the baseline and A-trap scenario.

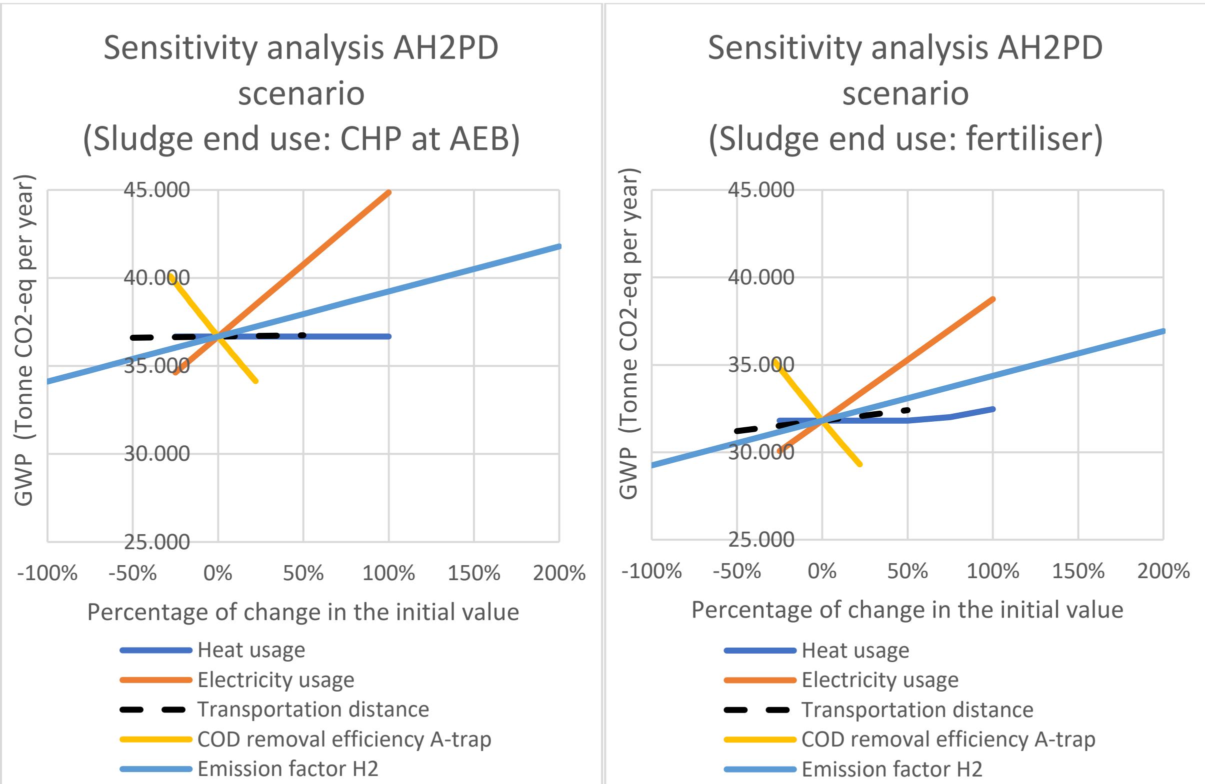


**FIGURE 36: SENSITIVITY ANALYSIS $AH_2PD$ SCENARIO**

## 7.2 Sensitivity analysis on modelling assumptions

This part of the sensitivity analysis is performed on four modelling assumptions; Allocation method, biogas usage, crediting excess heat and excluding biogenic $CO_2$. Furthermore, the effect of the exergy allocation in combination with excluding biogenic CO2 is modelled. The effect of the change in modelling assumption is explained and visualised underneath. Section 7.2.1 until and including 7.2.3 include biogenic $CO_2$. Section 7.2.4 and 7.2.5 exclude biogenic $CO_2$.

### 7.2.1 Allocation method

As explained in the methodology, using a different allocation method can significantly influence the results. Figure 37 shows the GWP per scenario in case of exergy allocation. The results are presented in kg $CO_2$-eq per GJ of exergy produced (kg $CO_2$-eq/$GJ_{ex}$). The baseline scenario is still the worst-performing scenario. This scenario has a net exergy consumption. The A-trap scenario is the second worst-performing scenario. Compared to the $AH_{(x)}PD$ scenarios, the A-trap scenario has high GHG emissions and a low exergy production. This results in a GWP of $1.5*10^3$ kg $CO_2$-eq/$GJ_{ex}$. It is noticeable that the $AH_{(x)}PD$ scenarios perform between 78% and 84% better than the A-trap scenario using exergy allocation, while they performed between 20% and 32% better than the A-trap scenario using substitution. In contrast to the allocation based on substitution, the AHPD scenarios perform better (between $0.23*10^3$ and $0.24*10^3$ kg $CO_2$-eq/$GJ_{ex}$) than the $AH_2PD$ scenarios (between $0.32*10^3$ and $0.33*10^3$ kg $CO_2$-eq/$GJ_{ex}$). This is caused by the exergy losses in the conversion of $H_2$ into biomethane and surplus gas. Next to this, there are more exergy losses when the additional surplus gas produced with $AH_2PD$ is burned in a boiler producing heat. The fertiliser scenario does not significantly perform differently than when the digested sludge is burned in the CHP of AEB. This is because fertiliser does not produce exergy and is therefore not credited. The difference in GWP between the two types of end-use is can be explained by the marginal natural gas and electricity input and heat output of AEB.

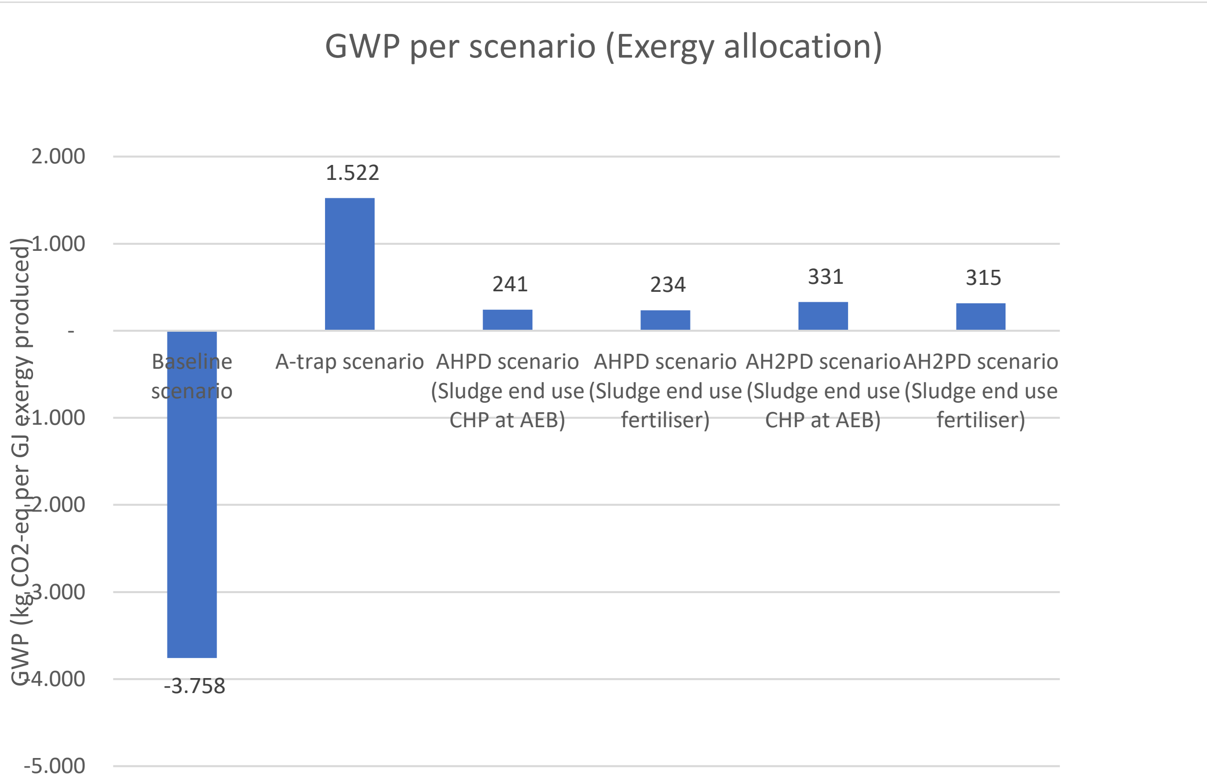


**FIGURE 37: GWP PER SCENARIO IN CASE OF EXERGY ALLOCATION**

### 7.2.2 Biogas usage

Figure 38 shows the GWP for the baseline and A-trap scenario in case 100% of the biogas is burned in a CHP. Under the current circumstances, 87% of the biogas is burned in a torch, which is probably caused by capacity problems at AEB. Solving these problems can result in a higher biogas input towards the CHP.  The blue bars show the GWP if 87% of the biogas is burned in a CHP and the orange bars show the GWP if 100% of the biogas is burned in a CHP. For the baseline scenario, the electricity consumption lowers when 100% of the biogas is burned in a CHP leading to a lower GWP. There is also a marginal increase in $CH_4$ emissions, increasing the GWP because a CHP emits more $CH_4$ than a torch. For the A-trap scenario, the effect of increasing the amount of biogas burned in a CHP is the same. However, since the biogas production is higher in the A-trap scenario, the effect is larger. The $AH_{(x)}PD$ scenarios are not shown in the figure since no gas is burned in a CHP or torch. The uncertainty in the amount of biogas burned in a CHP cannot make the GWP of the baseline or A-trap scenario lower than that of the $AH_{(x)}PD$ scenarios

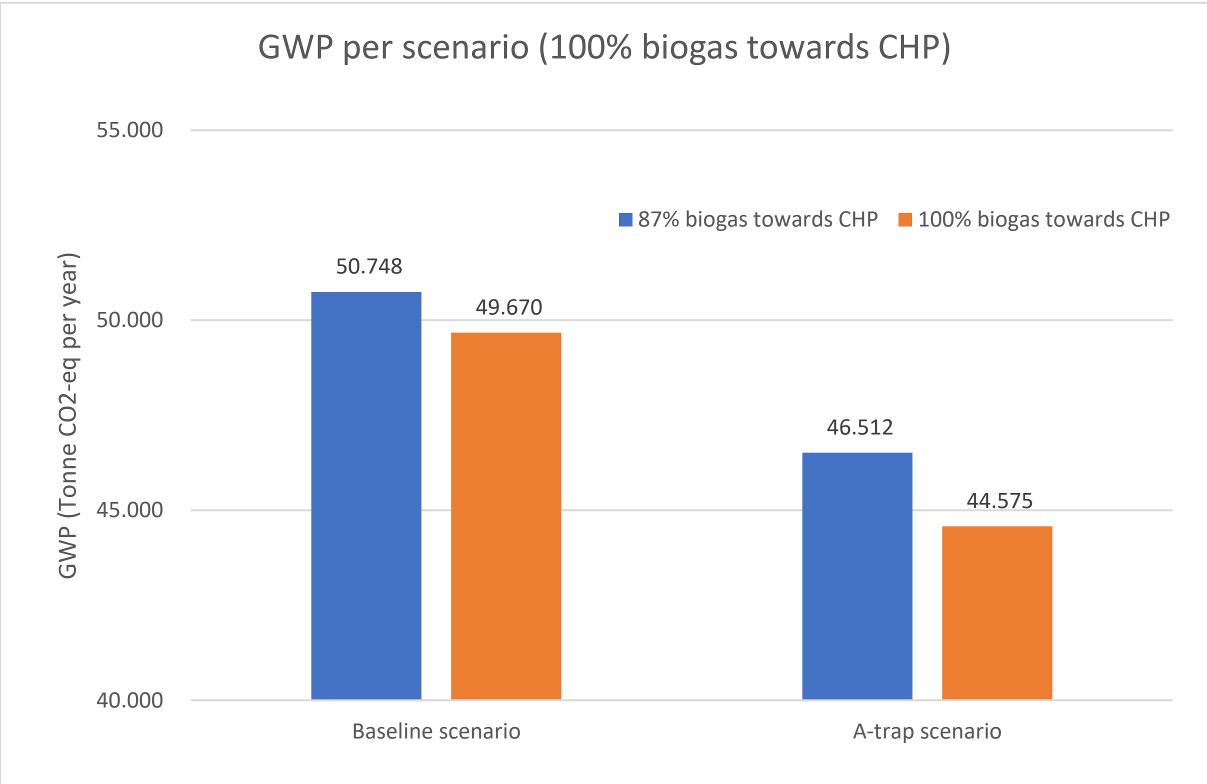


**FIGURE 38: GWP OF THE BASELINE AND A-TRAP SCENARIO IN CASE ALL BIOGAS IS BURNED IN A CHP**

### 7.2.3 Crediting of excess heat

Figure 39 shows the GWP per scenario in case excess heat is credited with a negative emission factor (see the orange bars). This impacts the A-trap scenario the most since this scenario produces the most excess heat. Crediting excess heat does not change the best performing scenario on the GWP. For $AH_{(x)}PD$, the scenarios with the sludge end-use at the CHP of AEB are impacted more than the scenarios with the sludge end-use as a fertiliser. This can be explained by the additional heat production in the CHP of AEB.

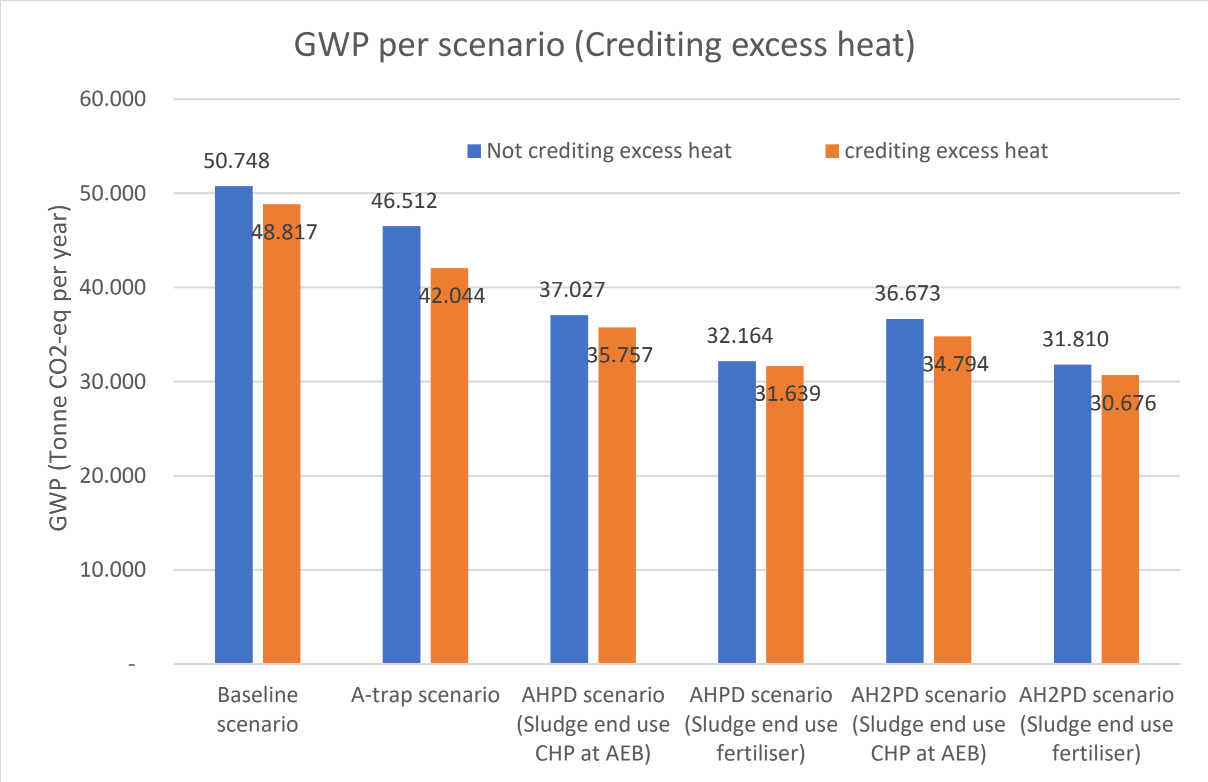


**FIGURE 39: GWP PER SCENARIO IN CASE EXCESS HEAT IS CREDITED**

### 7.2.4 Excluding biogenic $CO_2$

This section checks the impact of excluding biogenic $CO_2$ in the results of the LCA. As explained in the methodology, biogenic $CO_2$ is included in this research. Identifying biogenic $CO_2$ emission show all GHG emissions and shows the potential to reduce the GWP using CCU. Figure 40 shows the GWP per scenario with and without biogenic $CO_2$. The blue bars show the GWP including biogenic $CO_2$ and the orange bars show the GWP excluding biogenic $CO_2$. The baseline and A-trap scenario have two processes emitting biogenic $CO_2$; the biogas usage (in the CHP and torch) and the biological COD removal. Excluding the biogenic $CO_2$ reduces the GWP of the baseline scenario towards $12*10^3$ tonne $CO_2$-eq/year and reduces the GWP of the A-trap scenario towards $8*10^3$ tonne $CO_2$-eq/year. In both scenarios, the GWP mainly consists of methane emissions emitted in the CHP, the water- and the sludge line. The $AH_{(x)}PD$ scenarios have four processes emitting biogenic $CO_2$; the biomethane usage, the surplus gas usage (in a boiler), the biological COD removal and the dissolved $CO_2$ during $AH_{(x)}PD$. Excluding the biogenic $CO_2$ emissions results in a negative GWP of all $AH_{(x)}PD$ scenarios, showing it is possible to reduce the GWP during the process of cleaning wastewater. The $AH_{(x)}PD$ scenarios with the sludge end-use in the CHP of AEB have a GWP of between $-1*10^3$ and $0*10^3$ tonnes $CO_2$-eq/year. The $AH_{(x)}PD$ scenarios with the sludge end-use as a fertiliser have a GWP of between $-6*10^3$ and $-5*10^3$ tonne $CO_2$-eq/year. It is noticeable that the $AH_{(x)}PD$ scenarios perform between 102% and 150% better than the baseline scenario when biogenic CO2 is excluded, while they performed between 27% and 37% better than the baseline scenario when biogenic CO2 is included. Most important is that excluding biogenic $CO_2$ does not change the best performing scenario on the GWP.

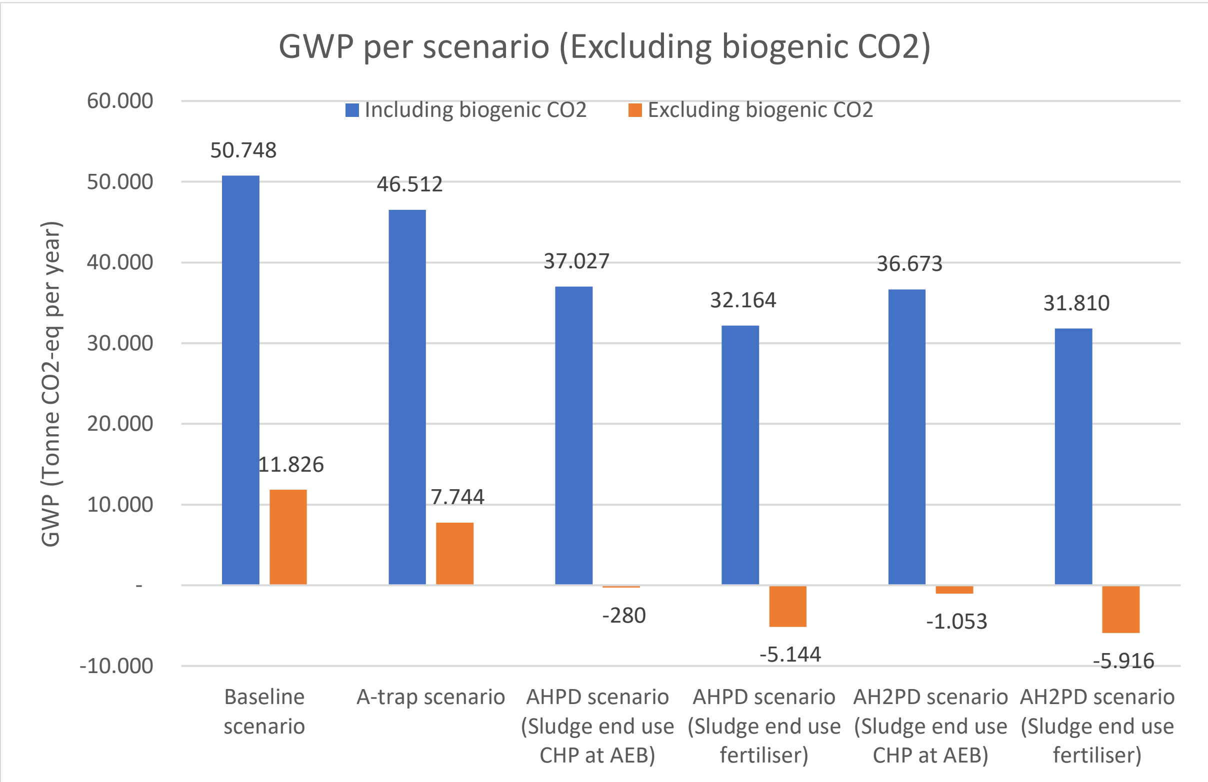


**FIGURE 40: GWP PER SCENARIO IN CASE BIOGENIC $CO_2$ IS EXCLUDED**

### 7.2.5 Excluding biogenic $CO_2$ in combination with exergy allocation

The modelling assumptions with the most impact on the results are the allocation method and the inclusion of biogenic $CO_2$. Figure 41 modelled the effect of the change in both modelling assumptions at the same time. The effect of changing one modelling assumption at a time is already explained in section 7.2.1 and section 7.2.4. Changing both modelling assumptions at the same time makes the AHPD scenario where the digested sludge is used in the CHP of AEB perform best. The fertiliser end-use performs worse since the avoided GHG emissions of fertiliser production are not credited with exergy allocation and the fossil GHG emissions of the fertiliser end-use are higher because of the increased transportation distance and weight.

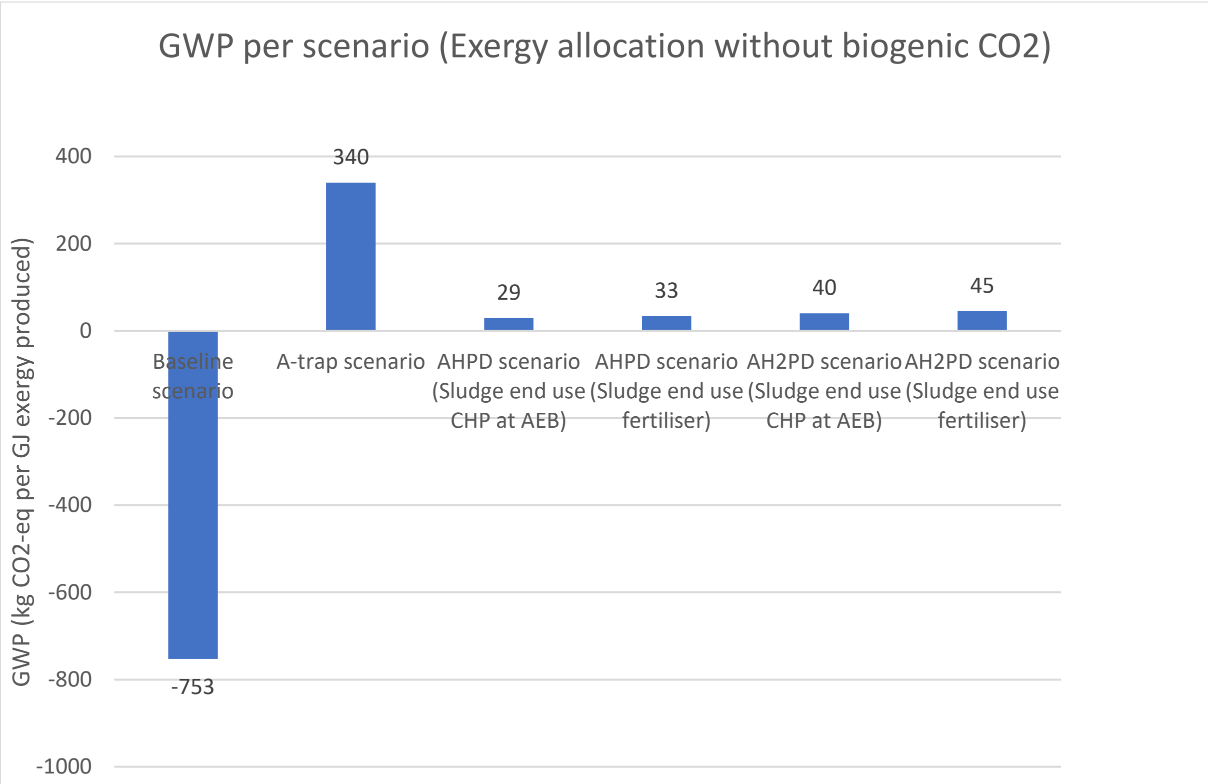


**FIGURE 41: GWP PER SCENARIO IN CASE OF EXERGY ALLOCATION AND EXCLUDING BIOGENIC $CO_2$**

# 8. Discussion

This section reflects the influence of the uncertainty from the data input and the uncertainty within the scenarios on the results. This is followed by the discussion of the methodological, theoretical and managerial implications.

## 8.1 Uncertainty from the input data

One major uncertainty from the input data of all scenarios is caused by the $N_2O$ emission factor. Currently, Dutch waterboards are allowed by the IPCC to report their $N_2O$ emissions based on one study in Durham performed in 1993, which resulted in an emission factor of 3.2 g $N_2O$/PE/year (Czepiel et al., 1995). This emission factor seems low, but because the $GWP_{100}$ of $N_2O$ is 298 times that of $CO_2$ (Winnipeg, 2012), a small increase in $N_2O$ emissions results in a much higher increase in $CO2_{eq}$ emissions. Kampschreur (2009) indicated that actual $N_2O$ emissions can be up to 28 times higher, which is based on measurements at multiple WWTPs. This research used the current emission factor of 3.2 g $N_2O$/PE/year and increased this in the sensitivity analysis to the maximum realistic emission factor proposed by Kampschreur (2009). This analysis showed the $N_2O$ emissions contribute to the GWP between $1*10^3$ tonne $CO_2$-eq/year and $25*10^3$ tonne $CO_2$-eq/year for all scenarios. $N_2O$ is emitted in the AT, which is located after the PST or A-trap. Currently, it is unknown if changing the PST for an A-trap results in different $N_2O$ emissions from the AT, which is assumed to be not the case. It is advised to do further research on the $N_2O$ emission factor, which should also include a different emission factor for a waterline with a PST than for a waterline with an A-trap. In the worst-case scenario, when the waterline including a PST has an $N_2O$ emission of $1*10^3$ tonne $CO_2$-eq/year and the waterline including an A-trap has an $N_2O$ emission of $25*10^3$ tonne $CO_2$-eq/year, the GWP of all scenarios consisting an A-trap is higher than the GWP of the baseline scenario. However, it is not likely that installing an A-trap increases $N_2O$ emissions.

The input data for the A-trap and the $AH_{(x)}PD$ scenarios contain additional uncertainties. A-traps can differ in their COD removal efficiency, leading to a different sludge output. The sensitivity analysis ranged the COD removal efficiency from the worst practice (53%) to the theoretical practice (90%). This showed that the A-trap and all $AH_{(x)}PD$ scenarios still have a lower GWP than the baseline scenario in case of the worst COD removal efficiency. The $AH_{(X)}PD$ scenarios have more uncertainty in the input data compared to the baseline and A-trap scenario. This is caused by the electricity and heat input of the $AH_{(x)}PD$ reactor, which is provided by an internal model from Bareau instead of full-scale measurements for the scenarios consisting of an AD. The Bareau model could not be verified in detail. Furthermore, the thickener in the AHPD installation (using autogenerated pressure) currently does not function. This may result in the requirement of another thickener, which increases the electricity demand. The electricity and heat demand were increased by 100% in the sensitivity analysis, which showed that, if one parameter doubles, all $AH_{(x)}PD$ scenarios still have a lower GWP than the baseline and A-trap scenario. However, it is advised to include better estimates of the electricity and heat demand in the model, after the first full-scale plant (located in Ameland) is operational. The ODS conversion and gas production of $AH_{(x)}PD$ is less uncertain. This is because the ODS conversion is calculated based on literature and the gas composition is based on measurements in the test reactor.

## 8.2 Uncertainty within the scenarios

Upgrading biogas produced with AD gained increased attention due to the rise in natural gas prices and sustainability targets (Petersson & Wellinger, 2009). The baseline and A-trap scenarios currently do not include the upgrading of the biogas since it is not the most used practice in the Netherlands. It is advised to do further research on the effect of upgrading the biogas on the GWP of the baseline and A-trap scenario. One positive effect of upgrading the biogas on the GWP would be the elimination of the overproduction of heat. It is advised to compare the effect on the GWP of this state-of-the-art technology with the GWP of the AHPD and $AH_2PD$ scenario.

As explained in the methodology, the $AH_{(x)}PD$ technologies have a lower TRL than the AD technology. The $AH_{(x)}PD$ technologies are tested in a pilot plant in which the performance is demonstrated (TRL 6), while the AD technology is already proven in an operational environment (TRL 9). Because of this, the $AH_{(x)}PD$ scenarios consists of more uncertainties than the A-trap and AD scenarios. One major uncertainty of the $AH_{(x)}PD$ scenarios is concerning the fertiliser end-use of the digested sludge. Since 1995, when new regulations concerning heavy metal concentrations were introduced, no waterboard in the Netherlands uses digested sludge as a fertiliser anymore (CBS, 2019). The scenarios consisting of $AH_{(x)}PD$ can potentially reduce the heavy metal concentration in the digested sludge since higher concentrations of metals are measured in the phosphor reactor (Bareau, 2020). However, since the concentration of heavy metals in the digested sludge was unknown during this research, both the end-use of the digested sludge at the CHP of AEB and the end-use of the digested sludge as fertiliser were included in this research. Before implementing any fertiliser end-use, it should be measured if the concentrations of the heavy metals in the digested sludge exceed the maximum concentration allowed in agriculture (see Table 1 of section 3.2.3). If no measurements took place, or if the concentration of heavy metals is higher than the maximum allowed concentration, it is not advised to implement any scenario with a fertiliser end-use. If the measurements do not exceed the maximum concentration allowed in agriculture, more research is needed on the optimal DS percentage of the sludge. Depending on the transportation distance, it may be better to dry the sludge further, reducing the transportation weight and therefore the transportation emissions.

## 8.3 Methodological implications

The different end-products of the scenarios were allocated using both substitution and exergy. The best performing scenario using allocation based on substitution is $AH_2PD$ with the sludge end-use as a fertiliser. However, If the hydrogen is produced with fossil fuel reforming, the AHPD scenario with the sludge end-use as a fertiliser performs better on the GWP. In the coming years, the emission factor of electricity, heat, and hydrogen may drop due to technological developments and the addition of more renewable energy sources, while the emission factor of burning NG will most likely remain equal. This would increase the performance on the GWP for the $AH_{(x)}PD$ scenarios, while it decreases the performance of the GWP for the baseline and A-trap scenario. The best performing scenario using exergy allocation is AHPD. Using this type of allocation, the end-use of the digested sludge only has a marginal influence on the GWP since exergy allocation does not credit the avoided fertiliser production. This makes this allocation method less suitable for the fertiliser end-use scenarios. It is recommended to include a hybrid allocation method (of substitution for the fertiliser and exergy for the other end-products) in further research. Since there was no available data about the heat temperature, the allocation based on exergy assumed that all produced heat has a temperature of 120◦C. For further research, it is advised to measure the temperature of all different heat sources and include this temperature in the exergy allocation.

In contrast to the common practice in the LCA community and IPCC standards, this research includes biogenic $CO_2$. This approach showed the total biogenic CO2 emissions. Furthermore, this approach showed the share of the total biogenic CO2 emissions, which is emitted due to the combustion of methane in energy-producing processes. The impact of excluding biogenic $CO_2$ on the results of each scenario is calculated for allocation based on substitution and exergy. The results for substitution showed that excluding biogenic $CO_2$ has no consequence on the order of performance on the GWP of the scenarios. However, excluding biogenic $CO_2$ resulted in a negative GWP for all $AH_{(x)}PD$ scenarios, showing it is possible to decrease the heat-trapping potential of the atmosphere during the process of cleaning wastewater. The results for exergy allocation showed that excluding biogenic $CO_2$ resulted in the change of the best end-use of the digested sludge. The AHPD scenario with the CHP at AEB end-use outperformed the fertiliser end-use since the avoided fertiliser production is not credited and the fertiliser end-use scenario has more fossil $CO_2$ emissions because of the increased transportation distance and weight.

The mass and energy flows, in the water-, sludge- and biogas line are modelled on a yearly basis. This was done because the input data from Waternet was provided per year. The downside of this approach is that the heat demand is modelled linear, while it should fluctuate based on the outside temperature. Modelling on a shorter time interval (e.g. daily) can result in a demand for external heat during colder days. The effect of an increase in heat consumption on the GWP is shown in the spider diagrams. These diagrams show that an increasing heat demand would increase the GWP of the $AH_{(x)}PD$ scenarios with the digested sludge end-use as a fertiliser the most. However, the best scenario is not likely to change in case of a higher heat demand.

## 8.4 Theoretical implications

Three additions to the theory are made in this research. First, this research added a simplified modelling method, based on COD flows, to existing theory. This modelling method differentiates itself from other methods, by integrating the water-, sludge- and biogas line into one model. Making the connection between the entire system, placed the treatment of wastewater into a new and broader perspective. This perspective helped, for example, to understand that placing only an A-trap does not significantly lower GHG emissions in the entire system since part the GHG reduction in the waterline is cancelled out by the increase in GHG emissions in the sludge- and biogas line. Second, this research added theoretical insights into the GWP of four different combinations of technologies treating wastewater. The GWP of the baseline scenario was defined, after which alterations to the technologies were made which include an A-trap in one scenario and an A-trap and AHPD or $AH_2PD$ in the other scenarios. The GWP of the new scenarios were visualised in comparison to the baseline scenario. This approach did not only show the GWP of all scenarios, but also placed the GHG reduction of the new technologies into perspective. Third, this research adds to the existing theory by quantifying the biogenic $CO_2$ emissions of different methods to treat wastewater. Waterboards traditionally only focused on treating the wastewater, but this focus is recently extended to also include the digestion of sludge (CBS, 2018). Including the biogenic $CO_2$ helps to extend this focus and adds to existing theory by identifying the unused potential of CCU.

## 8.5 Managerial implications

The results of the case study (Section 6.6) can be used by the municipality of Gaasperdam to compare and pick one scenario based on the GWP. These results indicate that the $AH_2PD$ scenarios have the lowest GWP. Measurements of the heavy metal concentrations in the digested sludge are needed to select the best end-use of the digested sludge. A fertiliser end-use is advised if the maximum concentration allowed in agriculture is not exceeded, otherwise, it is advised to burn the digested sludge in a CHP. The results of the case study were calculated based on the entire WWTP Amsterdam West. Two different scaling factors were used, indicating the range in the expected GWP for each scenario. If all scenarios scale the same way, the $AH_2PD$ scenario remains the scenario with the lowers GWP. Further research is needed on the scaling factor, and more importantly on the difference in scaling factors between the different scenarios.

The results of this study can be generalised to other Dutch waterboards. For waterboards in other (non-western) countries, it is advised to revise the results of this study. This is advised because the heat usage of digesters is climate specific. Furthermore, the wastewater composition can differ per area since it depends on the number of households, industry, the type of sewage and the weather. The results of this study were placed into a wider perspective, by calculation the maximum GHG reduction potential of $AH_{(x)}PD$ in the Netherlands. If the results of this study are directly generalised to all Dutch waterboards, the total GHG reduction potential of $AH_{(x)}PD$ is $800*10^3$ tonne per year. The total GHG emissions in the Netherlands were $194*10^6$ tonne in 2016 (Ruyssenaars et al., 2019). Based on this total, implementing the $AH_{(x)}PD$ technology has the potential to reduce 0.4% of the yearly Dutch GHG emissions.

The results of this study revealed low hanging fruit to reduce GHG emissions in WWTPs, which could potentially be used by policymakers to set regulations. This research found that methane emissions from the water and sludge line contribute between 13% (baseline scenario) and 28% ($AH_2PD$ scenario) to the GWP. It is advised to verify this empirically and to do further research on the reduction potential of these methane emissions. One hypothesis is that these emissions can be reduced if the sludge thickeners and buffers are covered and the methane is burned before it is released into the environment. This could hypothetically reduce the GWP of methane emissions from the water and sludge line by 96% since the GWP of carbon dioxide is 25 times lower than the GWP of methane. In case this hypothesis is confirmed, it is advised to implement regulations concerning methane emissions. Furthermore, the results of the sensitivity analysis show that under ideal and reported circumstances, the nitrous oxide emissions of WWTPs are insignificant. However, literature suggests that nitrous oxide emissions can realistically be up to 28 times higher than these circumstances. It is advised to make it compulsory for waterboards to measure nitrous oxide emissions. Furthermore, it is advised to let waterboards report nitrous oxide emissions based on measurements instead of the current ideal circumstances. This would help to set regulations later.

# 9. Conclusion

This research has modelled the entire process of wastewater treatment, including the water-, sludge- and biogas line. Furthermore, a cLCA was performed on the GHG emissions of different methods to treat wastewater. The GHG emission reduction potential, of an A-trap with or without $AH_{(x)}PD$, is calculated using the wastewater treatment plant Amsterdam West as a baseline. The first main research question is repeated and answered underneath.

**"How can the mass and energy flows of wastewater treatment be modelled and how can the change in mass and energy flows, caused by new technologies, be incorporated into this model?"**

The mass and energy flows were modelled based on the COD flows in the waterline, the ODS flows in the sludge line and the gas flows in the biogas line. This model was built from scratch and differentiate itself from other models by connecting the water-, sludge, and biogas line. The flows in the sludge-line were connected to the waterline by using the correlation between ODS and COD (1 ODS = 1.42 COD) indicated in literature. The correctness of this correlation was checked using the measurements of the COD output of the waterline and the ODS input of the sludge line for the baseline scenario. This correlation was found to be accurate. The connection of the biogas line to the sludge line was modelled based on the standard gas production per mass of ODS removed (taken from literature). The correctness of this gas production was checked using the calculated ODS removal in the AD and the measured gas production of the AD for the baseline scenario. It was found that the actual gas production was 11% lower than the expected gas production based on literature. Because of this, the gas production values of literature were corrected which made the new values match the actual production. Connecting the water, sludge and biogas line made it possible to calculate the change in mass and energy flows, caused by implementing a new technology, in the entire system. The mass and energy flows were shown in the flowcharts of section 5.3. The calculated mass and energy flows were needed as an input for the second research question, where the GHG emissions of all scenarios are compared. This second main research question and the corresponding sub-questions are repeated underneath, after which they are answered.

**"What is the greenhouse gas emission reduction potential of the autogenerative high-pressure digestion technology compared to the baseline scenario from a gate to grave perspective?"**

1. What are the greenhouse gas emissions to treat the wastewater of all population equivalents of Amsterdam west in the baseline scenario?
2. How do these emissions change if the PST is replaced by an A-trap?
3. How do these emissions change if the PST is replaced by an A-trap and the AD process is replaced by AHPD?
4. How do these emissions change if the PST is replaced by an A-trap and the AD process is replaced by $AH_2PD$?

The GWP for the entire WWTP Amsterdam west **including biogenic $CO_2$** is $51*10^3$ tonne $CO_2$-eq per year for the baseline scenario. Replacing the PST for the A-trap reduces these emissions towards $47*10^3$ tonne $CO_2$-eq per year. This is a reduction of 8% compared to the baseline scenario. If also the AD process is replaced by AHPD, the GHG emissions are reduced further towards a value between $32*10^3$ and $37*10^3$ tonne $CO_2$-eq per year. This corresponds with a reduction between 27% and 37% compared to the baseline scenario. In case the PST is replaced by an A-trap and the AD process is replaced by $AH_2PD$, the GHG emissions are reduced towards a value between $32*10^3$ and $37*10^3$ tonne $CO_2$-eq per year. This corresponds with a reduction between 28% and 37% compared to the baseline scenario. The variance in the GHG emissions is caused amongst others by the uncertainty in the end-use of the digested sludge from $AH_{(x)}PD$. The lower GHG emissions can be achieved in case the metal concentration in the digested sludge does not exceed the maximum concentration allowed in agriculture and could, therefore, be used as a fertiliser. In case the maximum allowed metal concentration is exceeded, the alternative end of life option modelled is burning sludge in a CHP, resulting in higher GHG emissions. **Excluding biogenic $CO_2$** results in a GWP for the entire WWTP Amsterdam West of $12*10^3$ tonne $CO_2$-eq per year for the baseline scenario, $8*10^3$ tonne $CO_2$-eq per year for the A-trap scenario, between $-5*10^3$ and $0*10^3$ tonne $CO_2$-eq per year for the AHPD scenario and between $-6*10^3$ and $-1*10^3$ tonne $CO_2$-eq per year for the $AH_2PD$ scenario. Compared to the baseline scenario, the GHG reduction potential is 35% for the A-trap scenario, between 102% and 143% for the AHPD scenario and between 109% and 150% for the $AH_2PD$ scenario. A reduction of more than 100% indicates that the heat trapping potential of the atmosphere decreases.

Ultimately, it can be concluded that the AHPD scenario can reduce the GHG emissions of wastewater treatment between 27% and 37% when biogenic $CO_2$ is included, and between 102% and 143% when biogenic $CO_2$ is excluded. The GHG reduction potential of $AH_2PD$ is between 28% and 37% when biogenic $CO_2$ is included, and between 109% and 150% when biogenic $CO_2$ is excluded. The effect of the most important uncertainties was modelled in the sensitivity analysis. This analysis showed that ranging one parameter at a time or changing one modelling assumption never makes the baseline or A-trap scenario outperform the AHPD and $AH_2PD$ scenarios.

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# Appendix 1. Conversion and emission factors

This appendix consists the underlying principles and/or calculations of the conversion and emission factors.

## 1.1 Conversion factors

Two conversion factors are calculated in this appendix. First a correction factor for the biogas production is calculated, after which the breakdown of ODS in the $AH_{(x)}PD$ reactor is calculated.

### 1.1.1 Correction factor biogas production

The correction factor for the biogas production is calculated based on the difference between the expected biogas production of WWTP Amsterdam west, and the actual biogas production of the WWTP in Amsterdam west. For the PST, it was calculated that the primary sludge produced contained 43.5 tonne COD/d and the surplus sludge contained 42.7 tonne COD/d. The composition of the external COD input towards the digestor is not known, therefore the same composition as the COD produced in the waterline is assumed. Using those values, it is calculated that 50.5% of the COD converted is from primary sludge, and 49.5% of the COD converted is from surplus sludge. Is does not matter to calculate this percentage based on COD since COD can be laniary converted in ODS by dividing it by 1.42 (Stora, 1981-16). The ODS conversion in Amsterdam west is 40.6 tonne/d. Using the primary and surplus sludge percentages, 20.5 tonne/d comes from ODS from primary sludge, and 20.2 tonne/d comes from ODS from surplus sludge. The gas production based on literature from Stowa (2011-16) is calculated in Formula 1.

$$[1]: Biogas\ production\ baseline\ scenario\ literature \\ = Primary\ ODS * biogas\ production\ primary\ ODS + Surplus\ ODS \\ * biogas\ production\ surplus\ ODS \\ = 20.5 \left(\frac{Tonne\ ODS}{d}\right) * 1100 \left(\frac{Nm3}{tonne\ ODS}\right) + 20.2 \left(\frac{tonne\ ODS}{d}\right) \\ * 700 \left(\frac{Nm3}{tonne\ ODS}\right) = 36{,}652\ Nm3/d$$

The measured biogas production in Amsterdam West is 32,462 Nm3/d (Waternet, 2015) and the calculated biogas production based on the Stowa (2011-16) is 36,652 Nm3/d. Bases on this difference, the biogas production based on primary and surplus sludge is multiplied by **0.89** (32,462 /36,652). Doing this makes the values from literature equal the measured data.

### 1.1.2 Breakdown of ODS

5Chen and Hashimoto (1980) developed a formula to calculate the ODS conversion of a digestion technology. This formula is shown underneath in Formula 2.

$$[2]: Percentage\ of\ breakdown\ ODS = R\ = \left(\frac{O-1}{O-1+K}\right) * B$$

**Where:**

R = Percentage of the breakdown of ODS
O = Sludge retention time (30 days for $AH_{(x)}PD$ (Bareau, 2020) / minimum sludge retention time (3 days)
K = Break down constant (Primary sludge = 1, surplus sludge = 1.5)
B = Maximum break down of ODS (Primary sludge = 65% (0.65), surplus sludge = 40% (0.40))

Filing in the formula resulted in a breakdown of primary sludge of 59% and a breakdown of surplus sludge of 34%. According to Fooij & Hofstede (2019), the breakdown of ODS is higher in practice since the formula does not include a temperature aspect. They argue that the breakdown of ODS from primary sludge should be 65% for $AH_{(x)}PD$. This research used a value of 65% for primary sludge. Furthermore, the breakdown of ODS from surplus sludge according to Chen and Hashimoto (1980) is increased. This is done using Formula 3.

$$[3]: Breakdown\ of\ surplus\ sludge = \frac{Breakdown\ of\ primary\ sludge\ according\ to\ de\ Fooij\ \&\ Hofsteden, 2019}{Breakdown\ of\ primary\ sludge\ according\ to\ Chen\ \&\ Hashimoto,\ 1980} * Breakdown\ of\ surplus\ sludge\ according\ to\ Chen\ \&\ Hashimoto,\ 1980 = \frac{65\ (\%)}{59\ (\%)} * 34\ (\%) = 38\%$$

In the $AH_{(x)}PD$ scenarios, 81% of the COD is produced by the A-trap (primary sludge) and 19% of the COD is produced by the ST (See Figure 17). The same shares are valid for ODS since COD can be converted to ODS by dividing it by 1.42 (Stora, 1981-16). The final breakdown percentage of ODS is calculated in Formula 4.

$$[4]: Average\ breakdown\ ODS\ AHPD\ and\ AH2PD = \frac{Share\ primary\ sludge\ (\%) * breakdown\ percentage\ primary\ sludge (\%)}{100\ (\%)} + \frac{Share\ surplus\ sludge\ (\%) * breakdown\ percentage\ surplus\ sludge (\%)}{100\ (\%)} = \frac{81\ (\%) * 65\ (\%)}{100\ (\%)} + \frac{19\ (\%)\ \%\ 38 (\%)}{100\ (\%)} = \mathbf{60}\%$$

## 1.2 Emission factors

This appendix consists of the calculations of all emission factors. The calculations correspond with the calculation numbers showed in Table 6. The emission factor for biological COD removal in combination with an A-trap is based on carbon balance between the baseline and the A-trap scenario.

$$[5]: emission\ factor\ biological\ COD\ removal\ (A - trap\ scenario) = \frac{C\ biological\ removed\ (A - trap\ scenario)}{Total\ biological\ COD\ removal\ (A - trap\ scenario)} * \frac{molar\ weight\ CO2}{molar\ weight\ C} * 1000 \left(\frac{g}{kg}\right) = \frac{14.0 \left(\frac{tonne\ C}{d}\right)}{54.0 \left(\frac{tonne\ COD}{d}\right)} * \left(\frac{44 \left(\frac{g\ CO2}{mol}\right)}{12 \left(\frac{g\ C}{mol}\right)}\right) * 1000 \left(\frac{g}{kg}\right) = 947.2 \frac{g\ CO2}{kg\ COD\ biological\ removed}$$

**Where:**

$$C\ biological\ removed\ (A - trap\ scenario) = C\ in\ gas\ (Baseline\ scenario) + C\ biological\ removed\ (Baseline\ scenario) + C\ in\ CH4\ leakage\ (Baseline\ scenario) - C\ in\ gas\ (A - trap\ scenario) - C\ in\ CH4\ leakage\ (A - trap\ scenario) = 11.2 + 18.0 + 0.6 - 15.2 - 0.7 = 14.0\ \frac{tonne\ C}{d}$$

$$C\ in\ gas\ (Baseline\ scenario)$$
$$= CO2\ emissions\ biogas * \frac{molar\ weight\ C}{molar\ weight\ CO2} + CH4\ emissions\ biogas * \frac{Molar\ weight\ C}{Molar\ weight\ CH4}$$
$$= 40.5\ \frac{tonne\ CO2}{d} * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{44\ \left(\frac{g\ CO2}{mol}\right)}\right) + 0.2\ \frac{tonne\ CH4}{d} * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}\right)$$
$$= 11.2\ \frac{tonne\ C}{d}$$

$$C\ biological\ removed\ (baseline\ scenario)$$
$$= Biological\ COD\ removed * emission\ factor\ COD\ removal * \frac{molar\ weight\ C}{molar\ weight\ CO2}$$
$$= 55.1\ \left(\frac{tonne\ COD}{d}\right) * 1.200\ \left(\frac{tonne\ CO2}{tonne\ COD}\right) * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{44\ \left(\frac{g\ CO2}{mol}\right)}\right) = 18.0\ \frac{tonne\ C}{d}$$

$$C\ in\ CH4\ leakage\ (baseline\ scenario)$$
$$= (CH4\ leakage\ waterline + CH4\ leakage\ sludge\ line) * \frac{Molar\ weight\ C}{Molar\ weight\ CH4}$$
$$= \left(0.2\ \left(\frac{tonne\ CH4}{d}\right) +\ 0.6\ \left(\frac{tonne\ CH4}{d}\right)\right) * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}\right) = 0.6\ \frac{tonne\ C}{d}$$

$$C\ in\ gas\ (A - trap\ scenario)$$
$$= CO2\ emissions\ biogas * \frac{molar\ weight\ C}{molar\ weight\ CO2} + CH4\ emissions\ biogas * \frac{Molar\ weight\ C}{Molar\ weight\ CH4}$$
$$= 55.0\ \frac{tonne\ CO2}{d} * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{44\ \left(\frac{g\ CO2}{mol}\right)}\right) + 0.3\ \frac{tonne\ CH4}{d} * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}\right)$$
$$= 15.2\ \frac{tonne\ C}{d}$$

$$C\ in\ CH4\ leakage\ (A - trap\ scenario)$$
$$= (CH4\ leakage\ waterline + CH4\ leakage\ sludge\ line) * \frac{Molar\ weight\ C}{Molar\ weight\ CH4}$$
$$= \left(0.1\ \left(\frac{tonne\ CH4}{d}\right) +\ 0.9\ \left(\frac{tonne\ CH4}{d}\right)\right) * \left(\frac{12\ \left(\frac{g\ C}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}\right) = 0.7\ \frac{tonne\ C}{d}$$

[6]: $CO2\ emissions\ torch = CO2\ part\ biogas + CO2\ part\ burning\ biogas = 785 + 1157 = \mathbf{1941}\ \left(\frac{g\ CO2}{Nm3\ biogas\ burned}\right)$

**Where:**

$$CO2\ part\ biogas = \frac{0.3994\ (mol\ \%\ CO2\ biogas) * 44\ \left(\frac{g\ CO2}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)}$$
$$= 785 \frac{g\ CO2}{Nm3\ \ biogas\ burned}$$

$$CO2\ part\ burning\ biogas$$
$$= \left( \frac{0.5993\ (mol\ \%\ CH4\ biogas) * 16\ \left(\frac{g\ CH4}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)} - 7.48\ \left(\frac{g\ CH4\ unburned}{nM3\ biogas\ burned}\right) \right) * \frac{44\ \left(\frac{g\ CO2}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)} = 1157 \frac{g\ CO2}{Nm3\ biogas\ burned}$$

$$[7]: CO2\ emissions\ CHP = CO2\ part\ biogas + CO2\ part\ burning\ biogas = 785 + 1151 = \mathbf{1936}\ \left(\frac{g\ CO2}{Nm3\ biogas\ burned}\right)$$

**Where:**

$$CO2\ part\ biogas = \frac{0.3994\ (mol\ \%\ CO2\ biogas) * 44\ \left(\frac{g\ CO2}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)}$$
$$= 785 \frac{g\ CO2}{Nm3\ \ biogas\ burned}$$

$$CO2\ part\ burning\ biogas$$
$$= \left( \frac{0.5993\ (mol\ \%\ CH4\ biogas) * 16\ \left(\frac{g\ CH4}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)} - 9{,}36\ \left(\frac{g\ CH4\ unburned}{nM3\ biogas\ burned}\right) \right) * \frac{44\ \left(\frac{g\ CO2}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)} = 1151 \frac{g\ CO2}{Nm3\ biogas\ burned}$$

$$[8]: CO2\ emissions\ surplusgas\ AHPD = CO2\ part\ surplusgas + CO2\ part\ burning\ surplusgas = 930 + 1013 = \mathbf{1944}\ \left(\frac{g\ CO2}{Nm3\ biogas\ burned}\right)$$

**Where:**

$$CO2\ part\ surplusas = \frac{0.474\ (mol\ \%\ CO2\ surplusgas) * 44\ \left(\frac{g\ CO2}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)}$$

$$= 930 \frac{g\ CO2}{Nm3\ \ biogas\ burned}$$

$$CO2\ part\ burning\ surplusgas$$

$$= \left(\frac{0.526\ (mol\ \%\ CH4\ surplusgas) * 16\ \left(\frac{g\ CH4}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)} - 7.48\ \left(\frac{g\ CH4\ unburned}{nM3\ surplusgas\ burned}\right)\right) * \frac{44\ \left(\frac{g\ CO2}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}$$

$$= 1013 \frac{g\ CO2}{Nm3\ surplusgas\ burned}$$

[9]: $CO2\ emissions\ surplusgas\ AH2PD$

$$= CO2\ part\ surplusgas + CO2\ part\ burning\ surplusgas = 883 + 1061$$

$$= \mathbf{1944}\ \left(\frac{g\ CO2}{Nm3\ surplusgas\ burned}\right)$$

**Where:**

$$CO2\ part\ surplusgas = \frac{0.45\ (mol\ \%\ CO2\ surplusgas) * 44\ \left(\frac{g\ CO2}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)}$$

$$= 883 \frac{g\ CO2}{Nm3\ \ surplusgas\ burned}$$

$$CO2\ part\ burning\ surplusgas$$

$$= \left(\frac{0.55\ (mol\ \%\ CH4\ surplusgas) * 16\ \left(\frac{g\ CH4}{mol}\right) * 1000\ \left(\frac{l}{m3}\right)}{22.4\ \left(\frac{l\ gas}{mol}\right)} - 7.48\ \left(\frac{g\ CH4\ unburned}{nM3\ surplusgas\ burned}\right)\right) * \frac{44\ \left(\frac{g\ CO2}{mol}\right)}{16\ \left(\frac{g\ CH4}{mol}\right)}$$

$$= 1061 \frac{g\ CO2}{Nm3\ surplusgas\ burned}$$

$$[10]: Natual\ gas\ combustion = \frac{56.7\left(\frac{kg\ CO2}{GJ}\right) * 31.65\ (\frac{MJ}{Nm3})}{1000\ (\frac{MJ}{GJ})}$$

$$= 1.795\frac{kg\ CO2}{Nm3\ natural\ gas\ burned}$$

$$[11]: Natual\ gas\ presurisation = 0.13\left(\frac{kWh}{Nm3}\right)\ (RVO, 2011) * 480\frac{g\ co2-eq}{kWh} = 62.4\ \frac{g\ CO2-eq}{m3}$$

# Appendix 2. Calculations waterline

This appendix consists of the calculations and/or data coming to the results of the mass and energy flow diagrams for the baseline and the A-trap scenario for the waterline. This appendix consists of the COD and waterflow (Q) calculations. The electricity usage of the waterline and sludge line are treated together, because most of the available electricity usage was not split out between the different processes. Therefore, the energy usage can be found in Appendix 4.

## 2.1 COD calculations baseline scenario

Table 9 shows the COD calculations for the baseline scenario for the waterline. If data was not provided by Waternet, the calculation number can be found in the table, and the calculation with the corresponding number can be found under the table.

**TABLE 9: COD CALCULATIONS PST**

| Parameter | COD value baseline scenario (tonne/d) | Source or calculation nr |
|---|---|---|
| New wastewater input PST | 91.4 | (Waternet, 2015) |
| Return flow input PST | 17.7 | 1 |
| Output PST | 43.5 | 2 |
| Input AT | 65.7 | (Waternet, 2015) |
| Output AT | 16.3 | 3 |
| Input ST | 49.3 | 4 |
| Output ST | 42.7 | 5 |
| Input to surface water | 6.6 | (Waternet, 2015) |

$$[1]: Return\ flow\ input\ PST = COD\ output\ PST + COD\ input\ AT - new\ wastewater\ input\ PST$$
$$= 43.5\left(\frac{tonne\ COD}{d}\right) + 65.7\left(\frac{tonne\ COD}{d}\right) - 91.4\left(\frac{tonne\ COD}{d}\right)$$
$$= 17.7\ (\frac{tonne\ COD}{d})$$

$$[2]: Output\ PST = \frac{Primary\ sludge\ production\ (Waternet\ AW, 2015) * Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981-16)}{days\ per\ year}$$
$$= \frac{11{,}175\left(\frac{tonne\ ODS}{year}\right) * 1{,}42\left(\frac{tonne\ COD}{tonne\ ODS}\right)}{365\ (\frac{d}{year})} = 43.5\ (\frac{tonne\ COD}{d})$$

$$[3]: Output\ AT = Input\ AT - Input\ ST = 65.7\left(\frac{tonne\ COD}{d}\right) - 49.3\left(\frac{tonne\ COD}{d}\right)$$
$$= 16.3\left(\frac{tonne\ COD}{d}\right)$$

$$[4]: Input\ ST = Output\ ST + Input\ to\ surface\ water$$
$$= 42.7\left(\frac{tonne\ COD}{d}\right) + 6.6\left(\frac{tonne\ COD}{d}\right) = 49.3\left(\frac{tonne\ COD}{d}\right)$$

$$[5]: Output\ ST = \frac{Surplus\ sludge\ production\ (Waternet\ AW, 2015) * Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981 - 16)}{days\ per\ year}$$

$$= \frac{10{,}988\ \left(\frac{tonne\ ODS}{year}\right) * 1{,}42\ \left(\frac{tonne\ COD}{tonne\ ODS}\right)}{365\ (\frac{d}{year})} = 42.7\ \left(\frac{tonne\ COD}{d}\right)$$

## 2.2 COD calculations A-trap, AHPD and AH$_2$PD scenario

The COD flows for the A-trap scenario are based on the COD removal percentage of the A-trap, AT and the ST. These values and their source of calculation number can be found in Table 10. The fraction of COD removed in the AT and ST is assumed to be equal to the baseline scenario.

**TABLE 10: COD REMOVAL EFFICIENCIES**

| Parameter | COD removal A-trap scenario (%) | Source or calculation nr |
|---|---|---|
| A-trap | 74% | [1](KNW, 2017) |
| AT | 25% | 6 |
| ST | 87% | 7 |

1: The COD removal efficiency of the A-trap in Dokhaven is used in this research. For more information, see the theory section.

$$[6]: COD\ removal\ \%\ AT = \frac{Output\ AT\ baseline\ situation}{Input\ AT\ baseline\ situation} = \frac{16.3\ \left(\frac{tonne\ COD}{d}\right)}{65.7\ \left(\frac{tonne\ COD}{d}\right)} = 0.25 = 25\%$$

$$[7]: COD\ removal\ \%\ ST = \frac{Output\ to\ surface\ water\ baseline\ situation}{Input\ ST\ baseline\ situation} = \frac{42.7\ \left(\frac{tonne\ COD}{d}\right)}{49.3\ \left(\frac{tonne\ COD}{d}\right)}$$

$$= 0.87 = 87\%$$

Bases on the new COD removal efficiencies, the new COD flows in case of an A-trap can be calculated. The results of this calculation can be found in Table 11. The corresponding calculation numbers can be found under the table.

**TABLE 11: COD CALCULATIONS A-TRAP**

| Parameter | COD flows A-trap scenario (tonne/d) | Source or calculation nr |
|---|---|---|
| New wastewater input A-trap | 91.4 | (Waternet, 2015) |
| Return flow input A-trap | [1]19.8 or 0 | (Based on allocation, see appendix 5) |
| Output A-trap | 82.3 | 9 |
| Input AT | 28.9 | 10 |
| Output AT | 7.2 | 11 |
| Input ST | 21.7 | 12 |
| Output ST | 18.8 | 13 |
| Input to surface water | 2.9 | 14 |

[1]As explained in section 5.4.3, there is no return flow for the AH$_{(x)}$PD scenarios. This difference is dealt with during the allocation.

$$[9]: Output\ A-trap = COD\ removal\ \%\ A-trap * (New\ wastewater\ input\ A-trap + Return\ flow\ input\ A-trap) = 74\% * (91.4\left(\frac{tonne\ COD}{d}\right) + 19.8\left(\frac{tonne\ COD}{d}\right) = 82.3\left(\frac{tonne\ COD}{d}\right)$$

$$[10]: Input\ AT = (100\% - COD\ removal\ \%\ A-trap) * (New\ wastewater\ input\ A-trap + Return\ flow\ input\ A-trap) = (100\% - 74\%) * (91.4\left(\frac{tonne\ COD}{d}\right) + 19.8\left(\frac{tonne\ COD}{d}\right) = 28.9\left(\frac{tonne\ COD}{d}\right)$$

$$[11]: Output\ AT = COD\ removal\ \%\ AT * Input\ AT = 25\% * 28.9\left(\frac{tonne\ COD}{d}\right) = 7.2\left(\frac{tonne\ COD}{d}\right)$$

$$[12]: Input\ ST = (100\% - COD\ removal\ \%\ AT) * Input\ AT = (100\% - 25\%) * 28.9\left(\frac{tonne\ COD}{d}\right) = 21.7\left(\frac{tonne\ COD}{d}\right)$$

$$[13]: Output\ ST = COD\ removal\ \%\ ST * Input\ ST = 87\% * 21.7\left(\frac{tonne\ COD}{d}\right) = 18.8\left(\frac{tonne\ COD}{d}\right)$$

$$[14]: Input\ to\ surface\ water = (100\% - COD\ removal\ \%\ ST) * Input\ ST = (100\% - 87\%) * 21.7\left(\frac{tonne\ COD}{d}\right) = 2.9\left(\frac{tonne\ COD}{d}\right)$$

## 2.3 Waterflow calculations Baseline, A-trap, AHPD and $AH_2PD$ scenario

The results of the waterflows can be found in Table 12. The calculations coming to these results can be found under the corresponding calculation number under the table. All calculations assume that the weight of 1 $m^3$ water = weight of 1 $m^3$ sludge = 1000 kg. The waterflows for the AH(x)PD scenarios are slightly lower than indicated in the Table, since there is no return flow from the centrifuge at $AH_{(x)}PD$. For AH(x)PD al waterflows (excepts for the new wastewater input) needs to be multiplied by the difference in wastewater input, which is 0.99 (177,897/(177,897+1915). This has almost no influence on the results and is therefore ignored.

**TABLE 12: WATERFLOWS PST AND A-TRAP**

| Parameter | Q baseline scenario ($m^3$/d) | Q A-trap, AHPD and $AH_2PD$ scenario ($m^3$/d) | Source or calculation nr |
|---|---|---|---|
| New wastewater input PST or A-trap | 177,897 | 177,897 | (Waternet, 2015) |
| Return flow input PST or A-trap | 1,616 | 1,915 (A-trap scenario)<br>0 ($AH_{(x)}PD$ scenarios) | [15] & [16] |
| Output PST or A-trap | 699 | 1 1,323 | [17] & [18] |
| Input AT | 176,899 | 176,574 | [19] & [20] |
| Output AT | 0 | 0 | N/A |

| | | | |
|---|---|---|---|
| Input ST | 176,899 | 176,574 | N/A |
| Output ST | 555 | 244 | [21] & [22] |
| Input to surface water | 176,344 | 176,329 | [23] & [24] |

[1]It is assumed that A-trap sludge has the same DS percentage as primary sludge from the PST.

$$[15]: Return\ flow\ input\ PST\ =\ Water\ flow\ input\ centrifuge - Water\ flow\ input\ CHP$$
$$= \frac{Sludge\ input\ AD\ (ODS + ADS)}{ds\ percentage} - \frac{Sludge\ input\ CHP\ (ODS + ADS)}{ds\ percentage\ (Waternet\ AW, 2015)}$$
$$= \frac{111.1\ \left(\frac{Tonne\ sludge}{d}\right)}{6.0\ (\%)} - \frac{52.9\ \left(\frac{Tonne\ sludge}{d}\right)}{22.4\ (\%)} = 1{,}616\frac{m3}{d}$$

$$[16]: Return\ flow\ input\ A - trap\ =\ Water\ flow\ input\ centrifuge - Water\ flow\ input\ CHP$$
$$= \frac{Sludge\ input\ AD\ (ODS + ADS)}{ds\ percentage} - \frac{Sludge\ input\ CHP\ (ODS + ADS)}{ds\ percentage\ \ (Waternet\ AW, 2015)}$$
$$= \frac{122.6\ \left(\frac{Tonne\ sludge}{d}\right)}{5.6\ (\%)} - \frac{57.9\ \left(\frac{Tonne\ sludge}{d}\right)}{22.4\ (\%)} = 1{,}915\frac{m3}{d}$$

$$[17]: Output\ PST\ = \frac{Sludge\ output\ PST}{ds\ percentage\ (Waternet\ AW, 2015)} = \frac{37.1\ \left(\frac{Tonne\ sludge}{d}\right)}{5.3\ (\%)} = 699\frac{m3}{d}$$

$$[18]: Output\ A - trap\ = \frac{Sludge\ output\ A - trap}{ds\ percentage\ PST\ (Waternet\ AW, 2015)} = \frac{70.2\ \left(\frac{Tonne\ sludge}{d}\right)}{5.3\ (\%)}$$
$$= 1{,}323\frac{m3}{d}$$

$$[19]: Input\ AT\ baseline\ situation$$
$$=\ New\ wastewater\ input\ PST + Return\ flow\ input\ PST - Output\ PST$$
$$= 175{,}981\frac{m3}{d} + 1{,}616\frac{m3}{d} - 699\frac{m3}{d} = 176{,}899\frac{m3}{d}$$

$$[20]: Input\ AT\ A - trap\ situation$$
$$=\ New\ wastewater\ input\ A - trap + Return\ flow\ input\ A - trap - Output\ A$$
$$- trap = 175{,}981\frac{m3}{d} + 1{,}915\frac{m3}{d} - 1{,}323\frac{m3}{d} = 176{,}574\frac{m3}{d}$$

$$[21]: Output\ ST\ baeline\ situation\ = \frac{Sludge\ output\ ST}{ds\ percentage\ (Waternet\ AW, 2015)}$$
$$= \frac{38.6\ \left(\frac{Tonne\ sludge}{d}\right)}{7.0\ (\%)} = 555\frac{m3}{d}$$

$$[22]: Output\ \ ST\ A - trap\ situation = \frac{Sludge\ output\ A - trap}{ds\ percentage\ (Waternet\ AW, 2015)}$$
$$= \frac{17.0\ \left(\frac{Tonne\ sludge}{d}\right)}{7.0\ (\%)} = 244\frac{m3}{d}$$

$$[23]: Input\ to\ surface\ water\ baseline\ situation$$
$$=\ Input\ ST\ baseline\ situation - Output\ ST\ baseline\ situation$$
$$= 176.899\frac{m3}{d} - 555\frac{m3}{d} = 176{,}344\frac{m3}{d}$$

$$[23]: Input\ to\ surface\ water\ A - trap\ situation$$
$$= \ Input\ ST\ A - trap\ situation - Output\ ST\ A - trap\ situation$$
$$= 176.574\frac{m3}{d} - 244\frac{m3}{d} = 176{,}329\frac{m3}{d}$$

# Appendix 3. Calculations sludge line

This appendix consists of the calculations and/or data coming to the results of the mass and energy flow diagrams for the sludge line. This appendix consists of the calculations for the sludge flows (ODS and IDS), the ds percentage of the sludge, the heat inputs, the transportation distance and weight, the biogas production including the $CO_2$ and $CH_4$ percentage, and the NG input to the CHP. In contrast to the calculations from the waterline, there are no different calculations for the sludge line for the A-trap scenario. This is the case since there are no processes changing in the sludge line, and the increased sludge input for the A-trap case is dealt with in the allocation. All calculations are based on the baseline scenario. The energy usage and production of the sludge line can be found in Appendix 4.

## 3.1 Sludge flows baseline scenario

The results of the sludge flows for the baseline scenario can be found in Table 13. The sludge input is the sum of the ODS and the IDS, this calculation is not shown under the table. The ODS, IDS and DS calculation number or source can be found in the right column of the table. The calculations with the corresponding calculation nr can be found under the table.

**Table 13: Sludge flows baseline scenario**

| Parameter | Sludge (tonne/d) | ODS (tonne/d) | IDS (tonne/d) | DS (%) | Source or calculation nr (ODS, IDS & DS) |
|---|---|---|---|---|---|
| Input AD from PST | 37.1 | 30.6 | 6.5 | 5.3 | [1], [2] & (Waternet, 2015) |
| Input AD from ST | 38.6 | 30.1 | 8.5 | 7.0 | [3], [4] & (Waternet, 2015) |
| External input AD | 35.4 | 28.2 | 7.3 | 5.7 | [5], [6] & [7] |
| Output AD | 40.6 | 40.6 | 0 | N/A | [8], N/A & N/A |
| Input centrifuge | 70.5 | 48.2 | 22.2 | 3.8 | [9], [10] & (Waternet, 2015) |
| Output centrifuge | 17.6 | 11.5 | 6.1 | 1.1 | [11], [12] & [13] |
| Input CHP | 52.9 | 36.7 | 16.1 | 22.4 | [14], [15] & (Waternet, 2015) |
| Input landfilling | 16.1 | 0 | 16.1 | 100 | N/A, N/A & N/A |

$$[1]: ODS\ input\ AD\ from\ PST = \frac{COD\ output\ PST}{Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981 - 16)}$$

$$= \frac{43.5\ \left(\frac{tonne\ COD}{d}\right)}{1{,}42\ \left(\frac{tonne\ COD}{tonne\ ODS}\right)} = 30.6\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[2]: IDS\ input\ AD\ from\ PST$$

$$= \frac{ODS\ input\ AD\ from\ PST}{100 - glow\ residue\ (Waternet\ AW, 2015)}$$

$$* glow\ residue\ (Waternet\ AW, 2015) = \frac{30.6\ \left(\frac{tonne\ ODS}{d}\right)}{100\ (\%) - 17\ (\%)} * 17\ (\%)$$

$$= 6.5\ \left(\frac{tonne\ IDS}{d}\right)$$

$$[3]: ODS\ input\ AD\ from\ ST = \frac{COD\ output\ ST}{Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981 - 16)}$$

$$= \frac{42.7\ \left(\frac{tonne\ COD}{d}\right)}{1{,}42\ \left(\frac{tonne\ COD}{tonne\ ODS}\right)} = 30.1\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[4]: IDS\ input\ AD\ from\ ST = \frac{ODS\ input\ AD\ from\ ST}{100 - glow\ residue\ (Waternet, 2015)} * glow\ residue\ (Waterne, 2015)$$

$$= \frac{30.1\ \left(\frac{tonne\ ODS}{d}\right)}{100\ (\%) - 22\ (\%)} * 22(\%) = 8.5\ (\frac{tonne\ IDS}{d})$$

$$[5]: External\ ODS\ input = \frac{Total\ ODS\ input\ (Waternet, 2015)}{days\ per\ year} - ODS\ input\ AD\ from\ PST - ODS\ input\ AD\ from\ ST$$

$$= \frac{32{,}438\ \left(\frac{tonne\ ODS}{year}\right)}{365\ \left(\frac{d}{year}\right)} - 30.6\ \left(\frac{tonne\ ODS}{d}\right) - 30.1\ \left(\frac{tonne\ ODS}{d}\right) = 28.2\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[6]: External\ IDS\ input = \frac{Total\ DS\ input\ (Waternet, 2015) - Total\ ODS\ input\ (Waternet, 2015)}{days\ per\ year} - IDS\ input\ AD\ from\ PST - IDS\ input\ AD\ from\ ST$$

$$= \frac{40{,}559\ \left(\frac{tonne\ DS}{year}\right) - 32{,}438\ \left(\frac{tonne\ ODS}{year}\right)}{365\ \left(\frac{d}{year}\right)} - 6.5\ \left(\frac{tonne\ IDS}{d}\right) - 8.5\ \left(\frac{tonne\ IDS}{d}\right) = 7.3\ \left(\frac{tonne\ IDS}{d}\right)$$

$$[7]: DS\%\ external\ input\ AD = \frac{External\ sludge\ input\ AD}{\left(\frac{Total\ water\ input\ AD\ (Waternet, 2015)}{days\ per\ year}\right) - Water\ output\ PST - Water\ output\ ST}$$

$$= \frac{35.4\ (\frac{tonne\ DS}{d})}{\frac{685{,}567\ (\frac{m3}{year})}{365\ (\frac{d}{year})} - 699\ \left(\frac{m3}{d}\right) - 555\ (\frac{m3}{d})} = 0.057 = 5.7\%$$

$$[8]: ODS\ output\ AD = ODS\ removal\ percentage\ (Watenet\ AW, 2015) * (ODS\ input\ PST + ODS\ input\ ST + Extenal\ ODS\ input)$$

$$= \frac{45.7\ (\%)}{100} * \left(30.6\ \left(\frac{tonne\ ODS}{d}\right) + 30.1\ \left(\frac{tonne\ ODS}{d}\right) + 28.2\ \left(\frac{tonne\ ODS}{d}\right)\right) = 40.6\ (\frac{tonne\ ODS}{d})$$

$$[9]: ODS\ input\ cetrifuge = ODS\ input\ PST + ODS\ input\ ST + Extenal\ ODS\ input - ODS\ output\ AD$$

$$= 30.6\ \left(\frac{tonne\ ODS}{d}\right) + 30.1\ \left(\frac{tonne\ ODS}{d}\right) + 28.2\ \left(\frac{tonne\ ODS}{d}\right) - 40.6\ \left(\frac{tonne\ ODS}{d}\right) = 48.2\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[10]: IDS\ input\ cetrifuge = IDS\ input\ PST + IDS\ input\ ST + Extenal\ IDS\ input$$
$$= 6.5 \left(\frac{tonne\ IDS}{d}\right) + 8.5 \left(\frac{tonne\ IDS}{d}\right) + 7.3 \left(\frac{tonne\ IDS}{d}\right) = 22.2 \left(\frac{tonne\ IDS}{d}\right)$$

$$[11]: ODS\ output\ centrifuge = ODS\ input\ centrifuge - ODS\ input\ CHP$$
$$= 48.2 \left(\frac{tonne\ ODS}{d}\right) - 36.7 \left(\frac{tonne\ ODS}{d}\right) = 11.5 \left(\frac{tonne\ ODS}{d}\right)$$

$$[12]: IDS\ output\ centrifuge = IDS\ input\ centrifuge - IDS\ input\ CHP$$
$$= 22.2 \left(\frac{tonne\ IDS}{d}\right) - 16.1 \left(\frac{tonne\ IDS}{d}\right) = 6.1 \left(\frac{tonne\ IDS}{d}\right)$$

$$[13]: DS\%\ output\ centrifuge = \frac{sludge\ output\ centrifuge}{return\ flow\ PST} = \frac{17.6 \left(\frac{tonne\ DS}{d}\right)}{1616 \left(\frac{m3}{d}\right)} = 0.011$$
$$= 1.1\%$$

$$[14]: ODS\ input\ CHP$$
$$= \left(1 - \frac{sludge\ removal\ percentage\ centrifuge\ (Waternet, 2015)}{100}\right)$$
$$* Sludge\ input\ centrifuge * \frac{ODS\ percentage\ to\ CHP\ (Waternet, 2015)}{100}$$
$$= \left(1 - \frac{25\ (\%)}{100}\right) * 70.5 \left(\frac{tonne\ DS}{d}\right) * \frac{30.5\ (\%)}{100} = 36.7 \left(\frac{tonne\ ODS}{d}\right)$$

$$[15]: IDS\ input\ CHP$$
$$= \left(\frac{sludge\ removal\ percentage\ centrifuge\ (Waternet, 2015)}{100}\right)$$
$$* Sludge\ input\ centrifuge * \frac{IDS\ percentage\ to\ CHP\ (Waternet, 2015)}{100}$$
$$= \left(\frac{25\ (\%)}{100}\right) * 70.5 \left(\frac{tonne\ DS}{d}\right) * \frac{69.5\ (\%)}{100} = 16.1 \left(\frac{tonne\ IDS}{d}\right)$$

## 3.2 Sludge flows A-trap scenario

The results of the sludge flows for the A-trap scenario can be found in Table 14. The sludge input is the sum of the ODS and the IDS, this calculation is not shown under the table. The ODS, IDS and DS calculation number or source can be found in the right column of the table. The calculations with the corresponding calculation nr can be found under the table.

**TABLE 14: SLUDGE FLOWS A-TRAP SCENARIO**

| Parameter | Sludge (tonne/d) | ODS (tonne/d) | IDS (tonne/d) | DS (%) | Source or calculation nr (ODS, IDS & DS) |
|---|---|---|---|---|---|
| Input AD from A-trap | 70.2 | 58.0 | 12.2 | 5.3 | [16], [17] & (assumption) |
| Input AD from ST | 17.0 | 13.3 | 3.8 | 7.0 | [18], [19] & (Waternet, 2015) |
| External input AD | 35.4 | 28.2 | 7.3 | 5.7 | [20], [21] & [22] |
| Output AD | 45.5 | 45.5 | 0 | N/A | [23], N/A & N/A |
| Input centrifuge | 77.2 | 53.9 | 23.3 | 4.0 | [24], [25] & (Waternet, 2015) |
| Output centrifuge | 19.3 | 12.6 | 6.7 | 1.0 | [26], [27] & [28] |
| Input CHP | 57.9 | 41.3 | 16.6 | 22.4 | [29], [30] & (Waternet, 2015) |
| Input landfilling | 16.6 | 0 | 16.6 | 100 | N/A, N/A & N/A |

$$[16]: ODS\ input\ AD\ from\ A-trap = \frac{COD\ output\ A-trap}{Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981-16)}$$

$$= \frac{82.3\left(\frac{tonne\ COD}{d}\right)}{1{,}42\ \left(\frac{tonne\ COD}{tonne\ ODS}\right)} = 58.0\ (\frac{tonne\ ODS}{d})$$

$$[17]: IDS\ input\ AD\ from\ A-trap$$

$$= \frac{ODS\ input\ AD\ from\ A-trap}{100-glow\ residue\ (Waternet, 2015)} * glow\ residue\ (Waternet, 2015)$$

$$= \frac{58.0\ \left(\frac{tonne\ ODS}{d}\right)}{100\ (\%)-17\ (\%)} * 17\ (\%) = 12.2\ (\frac{tonne\ IDS}{d})$$

$$[18]: ODS\ input\ AD\ from\ ST = \frac{COD\ output\ ST}{Conversion\ \ factor\ ODS\ to\ COD\ (\text{Stora}, 1981-16)}$$

$$= \frac{18.8\ \left(\frac{tonne\ COD}{d}\right)}{1{,}42\ (\frac{tonne\ COD}{tonne\ ODS})} = 13.3\ (\frac{tonne\ ODS}{d})$$

$$[19]: IDS\ input\ AD\ from\ ST$$

$$= \frac{ODS\ input\ AD\ from\ ST}{100-glow\ residue\ (Waternet, 2015)} * glow\ residue\ (Waternet, 2015)$$

$$= \frac{13.3\ \left(\frac{tonne\ ODS}{d}\right)}{100\ (\%)-22\ (\%)} * 22(\%) = 3.8\ (\frac{tonne\ IDS}{d})$$

$$[20]: External\ ODS\ input$$

$$= \frac{Total\ ODS\ input\ (Waternet, 2015)}{days\ per\ year} - ODS\ input\ AD\ from\ PST$$

$$- ODS\ input\ AD\ from\ ST$$

$$= \frac{32{,}438\ \left(\frac{tonne\ ODS}{year}\right)}{365\ \left(\frac{d}{year}\right)} - 30.6\ \left(\frac{tonne\ ODS}{d}\right) - 30.1\ \left(\frac{tonne\ ODS}{d}\right)$$

$$= 28.2\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[21]: External\ IDS\ input$$

$$= \frac{Total\ DS\ input\ (Waternet, 2015) - Total\ ODS\ input\ (Waternet, 2015)}{days\ per\ year}$$

$$- IDS\ input\ AD\ from\ PST - IDS\ input\ AD\ from\ ST$$

$$= \frac{40{,}559\ \left(\frac{tonne\ DS}{year}\right) - 32{,}438\ \left(\frac{tonne\ ODS}{year}\right)}{365\ \left(\frac{d}{year}\right)} - 6.5\ \left(\frac{tonne\ IDS}{d}\right)$$

$$- 8.5\ \left(\frac{tonne\ IDS}{d}\right) = 7.3\ \left(\frac{tonne\ IDS}{d}\right)$$

$$[22]: DS\%\ external\ input\ AD = \frac{External\ sludge\ input\ AD}{\left(\frac{Total\ water\ input\ AD\ (Waternet, 2015)}{days\ per\ year}\right) - Water\ output\ PST - Water\ output\ ST}$$

$$= \frac{35.4\ (\frac{tonne\ DS}{d})}{\frac{685{,}567\ (\frac{m3}{year})}{365\ (\frac{d}{year})} - 699\ \left(\frac{m3}{d}\right) - 555\ (\frac{m3}{d})} = 0.057 = 5.7\%$$

$$[23]: ODS\ output\ AD = ODS\ removal\ percentage\ (Watenet, 2015) * (ODS\ input\ A - trap + ODS\ input\ ST + Extenal\ ODS\ input)$$

$$= \frac{45.7\ (\%)}{100} * \left(58.0\ \left(\frac{tonne\ ODS}{d}\right) + 13.3\ \left(\frac{tonne\ ODS}{d}\right) + 28.2\ \left(\frac{tonne\ ODS}{d}\right)\right)$$

$$= 45.5\ (\frac{tonne\ ODS}{d})$$

$$[24]: ODS\ input\ cetrifuge = ODS\ input\ A - trap + ODS\ input\ ST + Extenal\ ODS\ input - ODS\ output\ AD$$

$$= 58.0\ \left(\frac{tonne\ ODS}{d}\right) + 13.3\ \left(\frac{tonne\ ODS}{d}\right) + 28.2\ \left(\frac{tonne\ ODS}{d}\right) - 44.5\ \left(\frac{tonne\ ODS}{d}\right) = 53.9\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[25]: IDS\ input\ cetrifuge = IDS\ input\ A - trap + IDS\ input\ ST + Extenal\ IDS\ input$$

$$= 12.2\ \left(\frac{tonne\ IDS}{d}\right) + 3.8\ \left(\frac{tonne\ IDS}{d}\right) + 7.3\ \left(\frac{tonne\ IDS}{d}\right)$$

$$= 23.3\ \left(\frac{tonne\ IDS}{d}\right)$$

$$[26]: ODS\ output\ centrifuge = \frac{ODS\ output\ centrifuge\ baseline\ scenario}{Sludge\ removed\ centrifuge\ baseline\ scenario * (ODS\ removal\ percentage\ centrifuge\ (Waternet, 2015) * Sludge\ output\ AD)} =$$

$$\frac{11.5\left(\frac{tonne\ ODS}{d}\right)}{17.6\ \left(\frac{tonne\ sludge}{d}\right) * 0.25\ (\%) * 77.2\ \left(\frac{tonne\ sludge}{d}\right)} = 19.3\ (\frac{tonne\ ODS}{d})$$

$$[27]: IDS\ output\ centrifuge = IDS\ input\ centrifuge - IDS\ input\ CHP$$

$$= 23.3\ \left(\frac{tonne\ IDS}{d}\right) - 16.6\left(\frac{tonne\ IDS}{d}\right) = 6.7\ (\frac{tonne\ IDS}{d})$$

$$[28]: DS\%\ output\ centrifuge = \frac{sludge\ output\ centrifuge}{return\ flow\ A - trap} = \frac{19.3\ (\frac{tonne\ DS}{d})}{1{,}915\ (\frac{m3}{d})} = 0.010$$

$$= 1.0\%$$

[29]: $ODS\ input\ CHP$

$$= \left(1 - \frac{sludge\ removal\ percentage\ centrifuge\ (Waternet, 2015)}{100}\right) * Sludge\ input\ centrifuge * \frac{ODS\ percentage\ to\ CHP}{100}$$

$$= \left(1 - \frac{25\ (\%)}{100}\right) * 77.2\ \left(\frac{tonne\ DS}{d}\right) * \frac{71\ (\%)}{100} = 41.3\ (\frac{tonne\ ODS}{d})$$

**Where:**

$$ODS\ percentage\ to\ CHP = \frac{ODS\ output\ AD - ODS\ removed\ centrifuge}{sludge\ output\ centrifuge} = \frac{53.9\ \left(\frac{tonne\ ODS}{d}\right) - 12.6(\frac{tonne\ ODS}{d})}{57.9\ (\frac{tonne\ sludge}{d})} = 71\ (\%)$$

[30]: $IDS\ input\ CHP$

$$= \left(\frac{sludge\ removal\ percentage\ centrifuge\ (Waternet\ AW, 2015)}{100}\right) * Sludge\ input\ centrifuge * \frac{100 - ODS\ percentage\ to\ CHP}{100}$$

$$= \left(\frac{25\ (\%)}{100}\right) * 77.2\ \left(\frac{tonne\ DS}{d}\right) * \frac{100 -\ 71.4\ (\%)}{100} = 16.6\ (\frac{tonne\ IDS}{d})$$

## 3.3 Sludge flows AHPD and $AH_2PD$ scenario

The results of the sludge flows for the AHPD and $AH_2PD$ scenario can be found in Table 15Table 14. The sludge input is the sum of the ODS and the IDS, this calculation is not shown under the table. The ODS, IDS and DS calculation number or source can be found in the right column of the table. The calculations with the corresponding calculation number can be found under the table.

**TABLE 15: SLUDGE FLOWS AHPD AND $AH_2PD$ SCENARIO**

| Parameter | Sludge (tonne/d) | ODS (tonne/d) | IDS (tonne/d) | DS (%) | Source or calculation nr (ODS, IDS & DS) |
|---|---|---|---|---|---|
| Input $AH_{(x)}PD$ from A-trap | 70.2 | 58.0 | 12.2 | 5.3 | (See appendix 3.2) |
| Input $AH_{(x)}PD$ from ST | 17.0 | 13.3 | 3.8 | 7.0 | (See appendix 3.2) |
| Output AHPD | 42.7 | 42.7 | 0 | N/A | [31], N/A & N/A |
| End-use fertiliser: Input fertiliser | 44.5 | 28.5 | 16.0 | 20 | [32], [33], (Bareau, 2020) |
| End-use CHP: Input CHP | 44.5 | 28.5 | 16.0 | 20 | [32], [33], (Bareau, 2020) |
| End-use CHP: Input landfilling | 16.0 | 0 | 16.0 | 100 | N/A, N/A & N/A |

[31]: $ODS\ output\ AH(x)PD$

$$= \frac{ODS\ removal\ efficiency\ AH(x)PD(See\ section\ 5.1)}{100} * (ODS\ input\ AH(x)PD\ A - trap + ODS\ input\ AH(x)PD\ ST)$$

$$= \frac{60\ (\%)}{100} * \left(58.0\ \left(\frac{tonne\ ODS}{d}\right) + 13.3\left(\frac{tonne\ ODS}{d}\right)\right) = 42.7\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[32]: ODS\ input\ AH(x)PD\ (fertiliser\ or\ CHP)$$
$$= \frac{100 - ODS\ removal\ efficiency\ AH(x)PD\ (See\ section\ 5.1)}{100}$$
$$* (ODS\ input\ AH(x)PD\ A - trap + ODS\ input\ AH(x)PD\ ST)$$
$$= \frac{100 - 60\ (\%)}{100} * \left(58.0\ \left(\frac{tonne\ ODS}{d}\right) + 13.3 \left(\frac{tonne\ ODS}{d}\right)\right)$$
$$= 28.5\ \left(\frac{tonne\ ODS}{d}\right)$$

$$[33]: IDS\ input\ AH(x)PD\ (fertiliser\ or\ CHP)$$
$$= IDS\ input\ from\ A - trap + IDS\ input\ from\ ST$$
$$= 12.2 \left(\frac{tonne\ IDS}{d}\right) + 3.8\ \left(\frac{tonne\ IDS}{d}\right) = 16.0\ \left(\frac{tonne\ IDS}{d}\right)$$

## 3.4 Transportation baseline, A-trap, AHPD and $AH_2PD$ scenario

The transportation of the sludge for all scenarios in tonne km is given in Table 16. The distance from the centrifuge towards the CHP of AEB is 2.2 km (Waternet, 2015). The ash and the fertiliser are transported over an estimated distance of 50 km. The digested sludge of AH(x)PD is transported differently depending on the end-use. The digested sludge will be transported to the CHP of AEB after which the ASH is transported over 50 km, or the digested sludge will be transported to agriculture. The calculations with the corresponding calculation nr can be found under the table.

**TABLE 16: TRANSPORTATION DISTANCE AND WEIGHT**

| | Centrifuge or AH(x)PD reactor to CHP (tonne km) | Ash from CHP to landfilling (tonne km) | AH(x)PD reactor to agriculture (tonne km) | Calculation nr |
|---|---|---|---|---|
| **Baseline scenario** | 520 | 807 | N/A | [34], [35], N/A |
| **A-trap scenario** | 570 | 829 | N/A | [36], [37], N/A |
| **$AH_{(x)}PD$ scenarios** | 489 | 800 | 11,122 | [38], [39], [40] |

$$[34]: transport\ distance\ centrifuge\ to\ CHP\ baseline\ scenario$$
$$= Distance * \frac{Sludge\ output\ centrifuge}{DS\ percentage\ sludge\ output\ centrifuge}$$
$$= 2.2\ (km) * \frac{52.9\ \left(\frac{Tonne}{d}\right)}{\left(\frac{22.4\ (\%)}{100}\right)} = 520\ Tonne * km$$

$$[35]: transport\ distance\ Ash\ to\ landfilling\ baseline\ scenario\ = Distance * IDS\ output\ CHP$$
$$= 50\ (km) * 16.1(\frac{Tonne}{d}) = 807\ Tonne * km$$

[36]: $transport\ distance\ centrifuge\ to\ CHP\ A - trap\ scenario$

$$= Distance * \frac{Sludge\ output\ centrifuge}{DS\ percentage\ sludge\ output\ centrifuge}$$

$$= 2.2\ (km) * \frac{57.9\ \left(\frac{Tonne}{d}\right)}{\left(\frac{22.4\ (\%)}{100}\right)} = 570\ Tonne * km$$

[37]: $transport\ distance\ Ash\ to\ landfilling\ A - trap\ scenario\ = Distance * IDS\ output\ CHP$

$$= 50\ (km) * 16.6(\frac{Tonne}{d}) = 829\ Tonne * km$$

[38]: $transport\ distance\ centrifuge\ to\ CHP\ AH(x)PD\ scenarios$

$$= Distance * \frac{Sludge\ output\ AH(x)PD}{DS\ percentage\ sludge\ output\ AH(x)PD}$$

$$= 2.2\ (km) * \frac{44.5\ \left(\frac{Tonne}{d}\right)}{\left(\frac{20\ (\%)}{100}\right)} = 489\ Tonne * km$$

[39]: $transport\ distance\ Ash\ to\ landfilling\ AH(x)PD\ scenarios$

$$= Distance * IDS\ output\ CHP = 50\ (km) * 16.0\left(\frac{Tonne}{d}\right) = 800\ Tonne * km$$

[40]: $transport\ distance\ AH(x)PD\ reactor\ to\ agriculture\ AH(x)PD\ scenarios$

$$= Distance * \frac{Sludge\ output\ AH(x)PD}{DS\ percentage\ sludge\ output\ AH(x)PD}$$

$$= 50\ (km) * \frac{44.5\ \left(\frac{Tonne}{d}\right)}{\left(\frac{20\ (\%)}{100}\right)} = 11{,}112\ Tonne * km$$

# Appendix 4. Calculations energy usage and production

This section shows the calculations of the heat, electricity and gas production and usage for all scenarios. Section 4.1 covers the heat balance, section 4.2 covers the electricity balance and the gas production is covered in section 4.3.

## 4.1 Heat

There are differences in heat usage and production between the different scenarios. Therefore, the scenarios are treated separately underneath.

### 4.1.1 Heat baseline scenario

In the baseline scenario, there are four processes which use or produce heat. The heat usage (in case of a negative value production) is listed in Table 17. The calculations with the corresponding calculation nr can be found under the table. It is assumed that half of the heat demand for the buildings is in the waterline (5 GJ/day), and the other half is used in the sludge line (5 GJ/day).

**TABLE 17: HEAT USAGE BASELINE SCENARIO**

| Process | Heat usage (GJ/d) | Calculation nr |
|---|---|---|
| **Buildings** | 10 (5 GJ waterline and 5 GJ sludge line) | [1] |
| **AD reactor** | 113 | [2] |
| **CHP of AEB burning the digested sludge** | -37 | [3] |
| **CHP burning the biogas** | -191 | (Waternet, 2015) |

$$[1]: Heat\ usage\ buildings = \frac{\%\ heat\ usage\ buildings\ of\ total\ (Stowa, 2013-03)}{100} * total\ heat\ usage\ WWTP\ (Waternet, 2015) = \frac{8\ (\%)}{100} * 123\left(\frac{GJ}{d}\right) = 10\frac{GJ}{d}$$

$$[2]: Heat\ usage\ AD\ reactor = \frac{\%\ heat\ usage\ AD\ reactor\ of\ total\ (Stowa, 2013-03)}{100} * total\ heat\ usage\ WWTP\ (Waternet, 2015) = \frac{92\ (\%)}{100} * 123\left(\frac{GJ}{d}\right) = \frac{113}{d}\ GJ$$

$$[3]: Heat\ production\ CHP\ burning\ the\ digested\ sludge = -Nett\ heat\ production\ AEB\ (IV-groep, 2017) * Sludge\ output\ centrifuge = -698\left(\frac{MJ}{tonne\ DS}\right) * 52.9\left(\frac{tonne\ DS}{d}\right) = -36{,}890\ MJ = -37\frac{GJ}{d}$$

### 4.1.2 Heat A-trap scenario

The heat usage of the A-trap scenario can be found in Table 18. The heat usage of the buildings is assumed to equal the heat consumption of the buildings in the baseline scenario. The heat usage of the other three parameters is recalculated to fit this scenario. The calculations with the corresponding calculation number can be found under the table.

**TABLE 18: HEAT USAGE A-TRAP SCENARIO**

| Process | Heat usage (GJ/d) | Calculation nr |
|---|---|---|
| **Buildings** | 10 (5 GJ waterline and 5 GJ sludge line) | (Same value as baseline) |
| **AD reactor** | 126 | [4] |
| **CHP of AEB burning the digested sludge** | -40 | [5] |
| **CHP burning the biogas** | -255 | [6] |

$$[4]: Heat\ usage\ AD\ reactor = Heat\ usage\ AD\ reactor\ baseline\ scenario * \left(\frac{ODS\ input\ AD\ A-trap\ scenario}{ODS\ input\ AD\ baseline\ scenario}\right) = 113(GJ) * \frac{99.4\left(\frac{Tonne}{d}\right)}{88.9\left(\frac{Tonne}{d}\right)} = 126\ GJ/d$$

$$[5]: Heat\ production\ CHP\ burning\ the\ digested\ sludge = -\ Nett\ heat\ production\ AEB\ (IV-groep, 2017) * Sludge\ output\ centrifuge = -698\left(\frac{MJ}{tonne\ DS*d}\right) * 57.9\ (Tonne\ DS) = -40{,}402\ MJ = -40\ GJ/d$$

$$[6]: Heat\ production\ CHP\ burning\ the\ biogas = Heat\ production\ baseline\ scenario * \frac{biogas\ production\ A-trap\ scenario}{Biogas\ production\ baseline\ scenario} = -191\left(\frac{GJ}{d}\right) * \frac{20{,}896\left(\frac{Nm3}{d}\right)}{28{,}877\left(\frac{Nm3}{d}\right)} = -255\frac{GJ}{d}$$

### 4.1.3 Heat AHPD and AH$_2$PD scenario

The heat usage of the AHPD and AH$_2$PD scenarios can be found in Table 19. The heat usage of the AHPD process is partly provided by Bareau and partly calculated. The calculations with the corresponding calculation nr can be found under the table.

**TABLE 19: HEAT USAGE AHPD AND AH$_2$PD SCENARIO**

| Process | Heat usage (GJ/d) | Calculation nr or source |
|---|---|---|
| **Buildings** | 10 (5 GJ waterline and 5 GJ sludge line) | (Same value as baseline scenario) |
| **AHPD reactor** | 65 | (Bareau, 2020) |
| **CHP of AEB burning the digested sludge** | -31 | [7] |
| **Boiler burning the surplus gas** | -89 AHPD, -114 AH$_2$PD | [8], [9] |
| **Annamox heat recovery** | -7.4 | (Bareau, 2020) |

$$[7]: Heat\ production\ CHP\ burning\ the\ digested\ sludge$$
$$= -\ Nett\ heat\ production\ AEB\ (IV - groep, 2017) * Sludge\ output\ AH(x)PD$$
$$= -698\ \left(\frac{MJ}{tonne\ DS * d}\right) * 44.5\ (Tonne\ DS) = -31{,}053\ MJ = -31\frac{GJ}{d}$$

$$[8]: Heat\ production\ boiler\ burning\ surplus\ gas\ AHPD$$
$$= Nm3\ methane\ in\ surplusgas * LHV\ methane * efficiency\ boiler$$
$$= 2{,}805\ \left(\frac{Nm3}{d}\right) * 35.4\ \left(\frac{MJ}{Nm3}\right) * \frac{90\ (\%)}{100} = 89{,}357\ MJ = 89\frac{GJ}{d}$$

$$[9]: Heat\ production\ boiler\ burning\ surplus\ gas\ AH2PD$$
$$= Nm3\ methane\ in\ surplusgas * LHV\ methane * efficiency\ boiler$$
$$= 3{,}593\ \left(\frac{Nm3}{d}\right) * 35.4\ \left(\frac{MJ}{Nm3}\right) * \frac{90\ (\%)}{100} = 114{,}489\ MJ = 114\frac{GJ}{d}$$

## 4.2 Electricity

Just like the heat demand, the electricity production and usage are covered separately for all scenarios.

### 4.2.1 Electricity baseline scenario

Waternet (2015) provided measurements about the energy usage, which are shown in Table 20. Literature was used to allocate the total electricity usage over the different processes since this data was not complete.

**TABLE 20: ELECTRICITY USAGE MEASUREMENTS (WATERNET, 2015)**

| Parameter | Value | Unit |
|---|---|---|
| Total electricity usage (water- and sludge line) | 20,177 | MWh/year |
| Electricity usage aeration | 7,735 | MWh/year |
| Electricity usage centrifuge | 1,614 | MWh/year |

Gude (2015) defined the share of the energy usage of the processes within the water- and sludge- line. This research did not include the electricity usage of the centrifuge and that of the CHP burning the digested sludge. This was not a problem since the electricity usage of the centrifuge was measured, and the electricity usage of the CHP is not included in the total electricity usage because the sludge is burned externally at AEB. The share of the energy usage of the different processes according to Gude (2015) can be found in Table 21.

**TABLE 21: ENERGY USAGE SHARE PER PROCESS (GUDE, 2015)**

| Parameter | Value | Unit | Allocated to |
|---|---|---|---|
| Aeration | 54.1 | % | AT |
| Clarifier | 3.2 | % | 50% PST and 50% ST (both have a clarifier) |
| Pumping | 14.3 | % | Fixed electricity usage waterline |
| Return sludge pumping | 0.5 | % | AT |
| Lighting and buildings | 8.1 | % | 50% energy usage waterline<br>50% energy usage sludge line |
| Chlorination | 0.3 | % | AT |
| Belt press | 3.9 | % | ST |
| AD | 14.2 | % | AD |

| | | | |
|---|---|---|---|
| Gravity thickening | 0.1 | % | PST |
| Grit chambers | 1.4 | % | Fixed electricity usage waterline |

Two parameters not only use electricity, but also use heat. The parameters are the lighting and buildings and the AD. This heat usage is subtracted from the energy usage. The typical electricity usage for an AD installation is 2% of the total (Insel et al., 2016). The share of the total electricity usage for the lighting and buildings is calculated underneath in formula 10, by subtracting the heat demand.

$$[10]: Electricity\ share\ Lighting\ and\ buildings$$
$$= Energy\ share\ L\&B\ (\%) - \frac{heat\ usage\ L\&B\ (GJ)\ (Stowa, 2013-03)}{3{,}6\left(\frac{GJ}{MWh}\right) * \left((Total\ electricity\ \ WWTP\ AW\ \left(\frac{MWh}{year}\right) - electricity\ centrifuge\ \left(\frac{MWH}{year}\right)\right) * 365\ \left(\frac{d}{year}\right)}$$
$$= 0.081\ (\%) - \left(\frac{10\ GJ}{3{,}6\left(\frac{GJ}{MWh}\right) * (20{,}177 - 1{,}614) * 365}\right. = 2.7\%$$

The shares defined by Gude (2015) of the other processes are divided by 0.78 to make the total electricity share of all processes 100% again.  The new share of the electricity usage of the different processes can be found in Table 22.

**TABLE 22: ELECTRICITY USAGE PER PROCESS (GUDE, 2015; STOWA, 2013-03 & INSEL ET AL., 2016)**

| Parameter | Value | Unit | Allocated to | Source |
|---|---|---|---|---|
| Aeration | 69.5 | % | AT | (Gude, 2015) |
| Clarifier | 4.1 | % | 50% PST and 50% ST (both have a clarifier) | (Gude, 2015) |
| Pumping | 18.4 | % | Fixed electricity usage waterline | (Gude, 2015) |
| Return sludge pumping | 0.6 | % | AT | (Gude, 2015) |
| Lighting and buildings | 2.7 [1] | % | 50% energy usage waterline<br>50% energy usage sludge line | (Gude, 2015;<br>Stowa, 2013-03) |
| Chlorination | 0.4 | % | AT | (Gude, 2015) |
| Belt press | 5.0 | % | ST | (Gude, 2015) |
| AD | 2.0 | % | AD | (Insel et al., 2016) |
| Gravity thickening | 0.1 | % | PST | (Gude, 2015) |
| Grit chambers | 1.8 | % | Fixed electricity usage waterline | (Gude, 2015) |

The electricity shares need to be allocated since literature did not include the external inputs in the water and sludge line at the WWTP Amsterdam West.  All values are divided by the allocation factor for the water- and/or the sludge line, which was calculated in section 5.5. Hereafter all shares are multiplied by 1.13 to make the total 100% again. The results of this calculation can be found in Table 23. The calculations with the corresponding calculation number can be found under the table.

**TABLE 23: ALLOCATED ELECTRICITY USAGE SHARE PER PROCES**

| Parameter | Value | Unit | Calculation nr |
|---|---|---|---|
| Aeration | 65.4 | % | [11] |
| Clarifier | 3.9 | % | [11] |

| | | | |
|---|---|---|---|
| Pumping | 17.3 | % | [11] |
| Return sludge pumping | 0.6 | % | [11] |
| Lighting and buildings | 3.1 | % | [12] |
| Chlorination | 0.4 | % | [11] |
| Belt press | 4.7 | % | [11] |
| AD | 2.8 | % | [13] |
| Gravity thickening | 0.1 | % | [11] |
| Grit chambers | 1.7 | % | [11] |

$$[11]: Waterline = \frac{Old\ value}{Alocation\ factor\ waterline} * factor\ to\ make\ the\ total\ 100\%$$
$$= \frac{x\ (\%)}{0{,}942\ (\%)} * 1.13$$

$$[12]: Waterline\ and\ sludgeline$$
$$= \left(\frac{\left(\frac{Old\ value}{2}\right)}{Alocation\ factor\ waterline} + \frac{\left(\frac{Old\ value}{2}\right)}{Alocation\ factor\ \ sludge\ line}\right)$$
$$* factor\ to\ make\ the\ total\ 100\% = \left(\frac{0.5\ *\ x\ (\%)}{0{,}942\ (\%)} + \frac{0.5\ *\ x\ (\%)}{0{,}644\ (\%)}\right) * 1.13$$

$$[13]: Sludgeline = \frac{Old\ value}{Alocation\ factor\ sludge\ line} * factor\ to\ make\ the\ total\ 100\%$$
$$= \frac{x\ (\%)}{0{,}644\ (\%)} * 1.13$$

The adapted literature needs one more conversion to be usable for the water- and sludge- line of Amsterdam west. The measured electricity usage for the aeration is used now, and all other percentages are adapted to make the total 100% again. The results can be found in Table 24. The corresponding formulas can be found under the table.

**TABLE 24: ADAPTED ALLOCATED ELECTRICITY USAGE PER PROCES (BASED ON MEASURED AERATION)**

| Parameter | Value | Unit | Calculation nr |
|---|---|---|---|
| Aeration | 41.7 | % | [14] |
| Clarifier | 6.5 | % | [15] |
| Pumping | 29.2 | % | [15] |
| Return sludge pumping | 1.0 | % | [15] |
| Lighting and buildings | 5.3 | % | [15] |
| Chlorination | 0.6 | % | [15] |
| Belt press | 8.0 | % | [15] |
| AD | 4.6 | % | [15] |
| Gravity thickening | 0.2 | % | [15] |
| Grit chambers | 2.9 | % | [15] |

$$[14]: Airation = \frac{Electricity\ usage\ aeration}{Total\ electricity\ usage - electricity\ usage\ centrifuge} * 100$$
$$= \frac{7{,}735\ \left(\frac{MWh}{year}\right)}{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)} * 100\ (\%) = 38.3\%$$

$$[15]: Clarifier\ until\ and\ including\ grit\ chambers$$
$$= \frac{100 - new\ electricity\ usage\ airation}{100 - old\ electricity\ usage\ airation} * old\ value$$
$$= \frac{100 - 41.3\ (\%)}{100 - 65.4\ (\%)} * old\ value\ (\%)$$

Now the final electricity use of the different processes can be calculated. The results of this can be found in Table 25. The corresponding formulas can be found under the Table.

**TABLE 25: FINAL ELECTRICITY USAGE PER PROCESS**

| Stage | Value | Unit | Calculation nr |
|---|---|---|---|
| Fixed electricity usage waterline | 17.6 | MWh/d | [16] |
| PST | 1.8 | MWh/d | [17] |
| AT | 22.0 | MWh/d | [18] |
| ST | 5.7 | MWh/d | [19] |
| Fixed electricity usage sludge line | 1.3 | MWh/d | [20] |
| AD | 2.4 | MWh/d | [21] |

$$[16]: Fixed\ electricity\ usage\ waterline$$
$$= \left(pumping + \frac{lighting\ and\ buildings}{2} + grit\ chambers\right) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$
$$= \left(29.2(\%) + \frac{5.3\ (\%)}{2} + 2.9\ (\%)\right) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)}$$
$$= 17.6\ (\frac{MWh}{d})$$

$$[17]: PST = \left(\frac{Clarifier}{2} + Grativy\ thickening\right) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$
$$= \left(\frac{6.5\ (\%)}{2} + 0.2\ (\%)\right) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)} = 1.8\ (\frac{MWh}{d})$$

$$[18]: AT = (Airation + return\ sludge\ pumping + Chloriation) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$
$$= \left(41.7\ (\%) + 1.0\ (\%) + 0.6\ (\%)\right) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)}$$
$$= 22.0(\frac{MWh}{d})$$

$$[19]: ST = \left(\frac{Clarifier}{2} + Belt\ press\right) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$

$$= (\frac{6.5\ (\%)}{2} + 8.0\ (\%)) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)} = 5.7(\frac{MWh}{d})$$

$$[20]: Fixed\ electricity\ usage\ sludge\ line$$

$$= \left(\frac{lighting\ and\ buildings}{2}\right)$$

$$* \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$

$$= \left(\frac{5.3\ (\%)}{2}\right) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)} = 1.3\ (\frac{MWh}{d})$$

$$[21]: AD = (AD) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$

$$= (4{,}6\%) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)} = 2.4\ (\frac{MWh}{d})$$

The last stage is to include the electricity consumption of the centrifuge, the CHP burning the sludge and the electricity production of the CHP burning the biogas. The results of this can be found in Table 26. The corresponding calculations can be found under the table. The electricity production of the CHP burning the biogas was measured and calculated. The measured value was used in this research. The calculated value was 1.5 MWh/d lower, as can be seen from formula 24.

**TABLE 26: ELECTRICITY USAGE CENTRIFUGE, CHP BURNING SLUDGE AND CHP BURNING BIOGAS**

| Stage | Value | Unit | Calculation nr or source |
|---|---|---|---|
| Centrifuge (Usage) | 4.4 | MWh/d | [22] |
| CHP burning sludge (Usage) | 10.2 | MWh/d | [23] |
| CHP burning biogas (Production) | -64.1 | MWh/d | (Waternet, 2015), checked in formula [24] |

$$[22]: Centrifuge = \frac{electricity\ usage\ centrifuge\ (WWTP\ AW, 2015)}{365} = \frac{1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)}$$

$$= 4.4\ (\frac{MWh}{d})$$

$$[23]: CHP\ burning\ sludge = \frac{\text{Electricity usage CHP (IV groep, 2014)}}{1000} * \text{ds input CHP}$$

$$= \frac{193\ \left(\frac{kWH}{tonne\ ds}\right)}{1000\ \left(\frac{kWh}{MWh}\right)} * 52.9\ \left(\frac{tonne\ ds}{d}\right) = 10.2$$

$$[24]: CHP\ burning\ biogas$$

$$= Biogas\ production\ (WWTP\ AW, 2015) * \frac{share\ biogas\ towards\ CHP\ (WWTP\ AW, 2015)}{100} * \frac{CH4\ content\ biogas\ (WWTP\ AW, 2015)}{100} * LHV\ CH4 * \frac{electrical\ efficiency\ CHP\ (WWTP\ AW, 2015)}{100} * \frac{1}{3600}$$

$$= 32{,}462\left(\frac{Nm3}{d}\right) * \frac{87\ (\%)}{100} * \frac{59.9\ (\%)}{100} * 35.8\left(\frac{MJ}{Nm3}\right) * \frac{37.4\ (\%)}{100} * \frac{1}{3600\ \left(\frac{GJ}{MWh}\right)}$$

$$= 62.6\frac{MWh}{d}$$

### 4.2.2 Electricity A-trap scenario

In case of the A-trap, the electricity usage of the waterline changes. Also, the electricity usage of the sludge line changes by the increased sludge input. The new electricity usage including the calculations can be found in Table 27. The electricity usage of the A-trap in Dokhaven is used in this research and adapted for the population equivalents of the WWTP in Amsterdam West.

**TABLE 27: ELECTRICITY USAGE WATERLINE WITH A-TRAP**

| Parameter | Value | Unit | Calculation nr or source |
|---|---|---|---|
| Fixed electricity waterline | 17.6 | MWh/d | (Same value as baseline scenario) |
| A-trap | 13.2 | MWh/d | [25] |
| AT | 8.9 | MWh/d | [26] |
| ST | 2.5 | MWh/d | [27] |
| Fixed electricity sludge line | 1.3 | MWh/d | (Same value as baseline scenario) |
| AD | 2.6 | MWh/d | [28] |
| Centrifuge (Usage) | 4.9 | MWh/d | [29] |
| CHP burning sludge (Usage) | 11.2 | MWh/d | [30] |
| CHP burning biogas (Production) | -85.5 | MWh/d | [31] |

$$[25]: A - trap$$

$$= \frac{electricity\ usage\ A - trap\ (Stowa, 2017 - 27) * PE\ amsterdam\ west\ (WWTP\ AW, 2015)}{1000 * 365} + \frac{share\ gravity\ thickening\ (Table\ 15)}{100} * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365} * \frac{COD\ output\ A - trap}{COD\ output\ PST}$$

$$= \frac{5.23\left(\frac{kWh}{PE}\right) * 906{,}185\ (PE)}{1000\left(\frac{kWh}{MWh}\right) * 365\left(\frac{d}{year}\right)} + \frac{0.2\%}{100} * \frac{20{,}177\left(\frac{MWh}{year}\right) - 1{,}614\left(\frac{MWh}{year}\right)}{365\left(\frac{d}{year}\right)} * \frac{82.3\left(\frac{Tonne\ COD}{d}\right)}{43.5\left(\frac{Tonne\ COD}{d}\right)}$$

$$= 13.2\left(\frac{MWh}{d}\right)$$

Two factors influence the electricity usage of the AT, which are the lower COD input and the nitrification/denitrification process changing into the anammox process. The energy usage in the AT consist of the aeration, but also of return sludge pumping and chlorination. The electricity use of the aeration is influenced by both factors because anammox needs less air than nitrification/ denitrification and less COD to be oxidises also needs less aeration. The new electricity use of the AT is calculated by the change in TOD from the baseline to the A-trap scenario. No nitrogen flows were calculated during this research, therefore the assumption is made that 58% of the incoming nitrogen flow is removed in the AT. This assumption is used for the baseline and A-trap scenario and corresponds with literature about the nitrogen removal in the AT of a reference WWTP (Mininni et al., 2015). The electricity use for the return sludge pumping and chlorination is only influenced by the lower COD input.

$$[26]: AT = \left( Airation * \frac{TOD\ AT\ A-trap}{TOD\ AT\ baseline} + (return\ sludge\ pumping\ + Chloriation) * \frac{COD\ removed\ AT\ A-trap}{COD\ removed\ AT\ baseline} \right) * \frac{Total\ electricity\ usage - electricity\ usage\ centrifuge}{365}$$

$$= \left( 41.7\ (\%) * \left( \frac{16.9\ \left(\frac{tonne\ TOD}{d}\right)}{42.2\ \left(\frac{tonne\ TOD}{d}\right)} \right) + (1.0\ (\%) + 0.6\ (\%)) * ( \frac{7.2 \left(\frac{tonne\ COD}{d}\right)}{16.3\ \left(\frac{tonne\ COD}{d}\right)} \right) * \frac{20{,}177\ \left(\frac{MWh}{year}\right) - 1{,}614\ \left(\frac{MWh}{year}\right)}{365\ \left(\frac{d}{year}\right)} = 8.9 (\frac{MWh}{d})$$

**Where:**

$$TOD\ AT\ baseline = \frac{N\ removed\ AT\ (Minninni\ et\ al., 2015)}{100} * N\ in\ influent\ (Waternet\ AW, 2015) * \frac{4 * molar\ weight\ oxygen}{molar\ weight\ nitrogen} + COD\ removed\ AT$$

$$= \frac{58\ (\%)}{100} * 9.742\ \left(\frac{Tonne\ N}{d}\right) * \frac{4 * 16\ \left(\frac{g}{mol}\right)}{14 * \left(\frac{g}{mol}\right)} + 16.3\ \left(\frac{tonne\ COD}{d}\right)$$

$$= 42.2\ (\frac{tonne\ TOD}{d})$$

$$TOD\ AT\ A-trap = \frac{N\ removed\ AT\ (Minninni\ et\ al., 2015)}{100} * N\ in\ influent\ (Waternet\ AW, 2015) * \frac{1.5 * molar\ weight\ oxygen}{molar\ weight\ nitrogen} + COD\ removed\ AT$$

$$= \frac{58\ (\%)}{100} * 9.742\ \left(\frac{Tonne\ N}{d}\right) * \frac{1.5 * 16\ \left(\frac{g}{mol}\right)}{14 * \left(\frac{g}{mol}\right)} + 7.2\ \left(\frac{tonne\ COD}{d}\right)$$

$$= 16.9\ (\frac{tonne\ TOD}{d})$$

$$[27]: ST \ = \ Electricity\ usage\ ST\ baseline \ * \frac{COD\ output\ AT\ a-trap}{COD\ output\ AT\ baseline}$$

$$= 6.7 \left(\frac{MWh}{d}\right) * \frac{21.7 \left(\frac{Tonne\ COD}{d}\right)}{49.3 \left(\frac{Tonne\ COD}{d}\right)} = 2.5 \left(\frac{MWh}{d}\right)$$

$$[28]: AD \ = \ Electricity\ usage\ AD\ baseline\ scenario \ * \frac{ODS\ input\ AD\ A-trap\ scenario}{ODS\ input\ AD\ baseline\ scenario}$$

$$= 2.4 \left(\frac{MWh}{d}\right) * \frac{99.4 \left(\frac{tonne\ ODS}{d}\right)}{88.9 \left(\frac{tonne\ ODS}{d}\right)} = 2.6 \frac{MWh}{d}$$

$$[29]: centrifuge$$

$$= \ Electricity\ usage\ centrifuge\ baseline\ scenario$$

$$* \frac{ODS\ input\ centrifuge\ A-trap\ scenario}{ODS\ input\ centrifuge\ baseline\ scenario} = 2.4 \left(\frac{MWh}{d}\right) * \frac{53.9 \left(\frac{tonne\ ODS}{d}\right)}{48.2 \left(\frac{tonne\ ODS}{d}\right)}$$

$$= 4.9 \frac{MWh}{d}$$

$$[30]: CHP\ burning\ sludge = \frac{\text{Electricity usage CHP (IV groep, 2014)}}{1000} * \text{ds input CHP}$$

$$= \frac{193 \left(\frac{kWH}{tonne\ ds}\right)}{1000 \left(\frac{kWh}{MWh}\right)} * 57.9 \left(\frac{tonne\ ds}{d}\right) = 11.2$$

$$[31]: CHP\ burning\ biogas$$

$$= Electricity\ production\ CHP\ baseline\ scenario$$

$$* \frac{Biogasproduction\ A-trap\ scenario}{(Biogasproduction\ baseline\ scenario)} = -61.1 \left(\frac{MWh}{d}\right) * \frac{27{,}877 \left(\frac{Nm3}{d}\right)}{20{,}896 \left(\frac{Nm3}{d}\right)}$$

$$= -85.5 \frac{MWh}{d}$$

### 4.2.3 Electricity AHPD and AH$_2$PD scenario

The electricity usage of the waterline could be used from the A-trap scenario. The fixed electricity usage of the sludge line is assumed to be equal than that of the other scenarios. The electricity usage of AH$_{(x)}$PD and the annamox process is provided by Bareau.

**TABLE 28: ELECTRICITY USAGE WATERLINE WITH A-TRAP**

| Parameter | Value | Unit | Source |
|---|---|---|---|
| Fixed electricity waterline | 17.6 | MWh/d | (same value as A-trap scenario) |
| A-trap | 13.2 | MWh/d | (same value as A-trap scenario) |
| AT | 8.9 | MWh/d | (same value as A-trap scenario) |
| ST | 2.5 | MWh/d | (same value as A-trap scenario) |
| Fixed electricity sludge line | 1.3 | MWh/d | (same value as A-trap scenario) |
| AHPD and AH$_2$PD | 6.6 and 4.5 | MWh/d | (Bareau, 2020) |
| anammox | 0.25 | MWh/d | (Bareau, 2020) |

## 4.3 Gas production

This section shows all gasses produced and used in the different scenarios. The biogas or biomethane production not only depends on the amount of ODS input, but also on the type of ODS. The ODS from primary sludge produces more gas (1100 nM3/tonne ODS removed) than the ODS from surplus gas (1100 nM3/tonne ODS removed) (Stowa, 2011-16). Both factors are included in the allocation factor of the biogas line. Section 4.3.1 covers the biogas production and natural gas consumption of the baseline and A-trap scenario. Section 4.3.2 covers the biomethane and surplus gas production and the natural gas and hydrogen consumption of the AHPD and $AH_2PD$ scenario.

### 4.3.1 Gas production baseline and A-trap scenario

Table 29 shows the biogas production and the natural gas consumption of the baseline and the A-trap scenario. The calculations can be found under the corresponding calculation number under the table.

**TABLE 29: GAS PRODUCTION AND CONSUMPTION BASELINE AND A-TRAP SCENARIO**

| | Baseline scenario | A-trap scenario | Calculation nr or source |
|---|---|---|---|
| **Biogas (Nm3/d)** | [1]32,462 | [1]32,462 | (Waternet, 2015) |
| **Natural gas (Nm3/d)** | 238 | 260 | [1], [2] |

[1]The biogas production which is not allocated is equal for the baseline and A-trap scenario. However, when allocated, the production of biogas is higher for the A-trap scenario as for the baseline scenario. This is because of the increased sludge input to the AD and because of the change in sludge composition (more primary sludge compared to surplus sludge)

$$[1]: Natural\ gas\ consumption\ baseline\ scenario$$
$$= Natural\ gas\ input\ for\ the\ CHP\ burning\ the\ digested\ sludge\ (IV - Groep, 2014) * Amount\ of\ sludge\ entering\ the\ CHP$$
$$= 4.5\left(\frac{Nm3}{tonne\ ds}\right) * 52.9\left(\frac{tonne\ ds}{d}\right) = 238\frac{Nm3}{d}$$

$$[2]: Natural\ gas\ consumption\ A - trap\ scenario$$
$$= Natural\ gas\ input\ for\ the\ CHP\ burning\ the\ digested\ sludge\ (IV - Groep, 2014) * Amount\ of\ sludge\ entering\ the\ CHP$$
$$= 4.5\left(\frac{Nm3}{tonne\ ds}\right) * 57.9\left(\frac{tonne\ ds}{d}\right) = 260\frac{Nm3}{d}$$

### 4.3.1 Gas production AHPD and $AH_2PD$ scenario

Table 30 shows the biomethane and surplus gas production and the natural gas and hydrogen consumption of the baseline and the A-trap scenario. The calculations can be found under the corresponding calculation number under the table.

**TABLE 30: GAS PRODUCTION AND CONSUMPTION AHPD AND $AH_2PD$ SCENARIO**

| | AHPD scenario | $AH_2PD$ scenario | Calculation nr |
|---|---|---|---|
| **Biomethane (Nm3/d)** | 25,214 | 30,746 | [3], [7] |
| **Surplus gas (Nm3/d)** | 5,329 | 6,528 | [4], [8] |
| **$CO_2$ dissolved (Nm3/d)** | 9,297 | 2,565 | [5], [9] |
| **Natural gas (Nm3/d)** | [1]200 | [1]200 | [6], [6] |
| **Hydrogen (tonne/d)** | N/A | 2,8 | N/A, [10] |

[1]Threre is only a natural gas consumption in both scenarios if the digested sludge is burned in a CHP.

$$[3]: Biomethane\ production\ AHPD = \frac{Methane\ produced\ AHPD * share\ of\ the\ methane\ in\ the\ biomethane\ (Bareau, 2020)}{CH4\ concentration\ biomethane\ (Bareau, 2020)}$$

$$= \frac{25497\ \frac{Nm3\ CH4}{d} * 0{,}89\ (\%)}{0{,}90\ (\%)} = 25{,}214 \frac{Nm3\ biomethane}{d}$$

**Where:**

$$Methane\ produced\ AHPD = (Total\ gas\ production\ AHPD) * standart\ methane\ concentration\ of\ gas\ from\ sewage\ sludge\ (Stowa, 2011 - 16) = \left(39{,}839 \frac{Nm3}{d}\right) * \frac{64\ (\%)}{100} = 25{,}497 \frac{Nm3\ CH4}{d}$$

$$Total\ gas\ production\ AHPD = primary\ ODS\ removed * gas\ production\ primary\ ODS * correction\ factor\ gas\ production + surplus\ ODS\ removed * gas\ production\ surplus\ ODS * correction\ factor\ gas\ production = 37.7 \left(\frac{tonne\ ODS}{d}\right) * 1100 \left(\frac{NM3}{tonne\ primary\ ODS}\right) * 0{,}89\ (\%) + 5.1 \left(\frac{tonne\ ODS}{d}\right) * 700 \left(\frac{NM3}{tonne\ surplus\ ODS}\right) * 0{,}89\ (\%) = 39{,}839 \frac{Nm3}{d}$$

$$[4]: surplusgas\ production\ AHPD = \frac{Methane\ produced\ AHPD * share\ of\ the\ methane\ in\ the\ surplusgas\ (Bareau, 2020)}{CH4\ concentration\ surplusgas\ (Bareau, 2020)}$$

$$= \frac{25497\ \frac{Nm3\ CH4}{d} * 0{,}11\ (\%)}{0{,}53\ (\%)} = 5{,}329 \frac{Nm3\ surplusgas}{d}$$

$$[5]: CO2\ disolved\ AHPD = CO2\ produced\ AHPD - CO2\ in\ biomethane - CO2\ in\ surplusgas = 14{,}342 \left(\frac{Nm3}{d}\right) - 2{,}521 \left(\frac{Nm3}{d}\right) - 2{,}524 \left(\frac{Nm3}{d}\right) = 9{,}297 \frac{Nm3\ CO2}{d}$$

**Where:**

$$CO2\ produced\ AHPD = total\ gas\ production\ AHPD * standart\ CO2\ concentration\ of\ gas\ from\ sewage\ sludge\ (Stowa, 2011 - 16) = 39{,}839 \left(\frac{Nm3}{d}\right) * \frac{36\ (\%)}{100} = 14{,}342 \frac{Nm3\ CO2}{d}$$

$$CO2\ in\ biomethane = Biomethane\ production\ AHPD * CO2\ percentage\ biomethane\ (Bareau, 2020) = 25{,}214 * \frac{10\ (\%)}{100} = 2{,}521 \frac{Nm3\ CO2}{d}$$

$$CO2\ in\ surplusgas$$
$$= \ Surpusgas\ production\ AHPD$$
$$*\ CO2\ percentage\ surplusgas\ (Bareau, 2020) = 5{,}329 * \frac{47{,}4\ (\%)}{100}$$
$$= 2{,}524\ \frac{Nm3\ CO2}{d}$$

$$[6]: Natural\ gas\ consumption\ AHPD\ and\ AH2PD\ scenario$$
$$= \ Natural\ gas\ input\ for\ the\ CHP\ burning\ the\ digested\ sludge\ (IV$$
$$- Groep, 2014) * \ Amount\ of\ sludge\ entering\ the\ CHP$$
$$= \ 4.5\left(\frac{Nm3}{tonne\ ds}\right) * 44.5\ \left(\frac{tonne\ ds}{d}\right) = 200\frac{Nm3\ NG}{d}$$

$$[7]: Biomethane\ production\ AH2PD$$
$$= \frac{(CH4\ produced\ AHPD + Aditional\ CH4\ by\ H2\ injection) * \%\ of\ the\ CH4\ in\ the\ biomethane\ (Bareau, 2020}{CH4\ concentration\ biomethane\ (Bareau, 2020)}$$
$$= \frac{(25497\ \frac{Nm3\ CH4}{d} + 7{,}171\frac{Nm3\ CH4}{d})\ * 0{,}89\ (\%)}{0{,}95\ (\%)} = 30{,}747\frac{Nm3\ biomethane}{d}$$

**Where:**

$$Aditional\ CH4\ by\ H2\ injection$$
$$= CO2\ produced\ AHPD * \%\ CO2\ converted\ to\ CH4\ (Bareau, 2020)$$
$$= 14{,}342\ \left(\frac{Nm3\ CO2}{d}\right) * \frac{50\ (\%)}{100} = 7{,}171\ \frac{Nm3\ CH4}{dn}$$

$$[8]: surplusgas\ production\ AH2PD$$
$$= \frac{(CH4\ produced\ AHPD + Aditional\ CH4\ by\ H2\ injection) * share\ of\ the\ CH4\ in\ surplusgas\ (Bareau, 2020)}{CH4\ concentration\ surplusgas\ (Bareau, 2020)}$$
$$= \frac{25497\ \frac{Nm3\ CH4}{d} * 0{,}11\ (\%)}{0{,}55\ (\%)} = 6{,}528\frac{Nm3\ surplusgas}{d}$$

$$[9]: CO2\ disolved\ AH2PD$$
$$= CO2\ produced\ AHPD - CO2\ in\ biomethane - CO2\ in\ surplusgas$$
$$- \ CO2\ converted\ to\ CH4\ by\ H2\ injection$$
$$= 14{,}342\left(\frac{Nm3}{d}\right) - 1{,}671\left(\frac{Nm3}{d}\right) - 2{,}935\ \left(\frac{Nm3}{d}\right) - 7{,}171\left(\frac{Nm3}{d}\right)$$
$$= 2{,}565\ \frac{Nm3\ CO2}{d}$$

**Where:**

$$CO2\ in\ biomethane$$
$$= \ Biomethane\ production\ AH2PD$$
$$*\ CO2\ percentage\ biomethane\ (Bareau, 2020) = 30{,}746 * \frac{5.4\ (\%)}{100}$$
$$= 1{,}671\ \frac{Nm3\ CO2}{d}$$

$$CO2\ in\ surplusgas$$
$$= \ Surpusgas\ production\ AH2PD$$
$$*\ CO2\ percentage\ surplusgas\ (Bareau, 2020) = 6{,}528 * \frac{45.0\ (\%)}{100}$$
$$= 2{,}935\ \frac{Nm3\ CO2}{d}$$

$$CO2\ converted\ to\ CH4\ by\ H2\ injection$$
$$= CO2\ produced\ AHPD * \%\ CO2\ converted\ to\ CH4\ (Bareau, 2020)$$
$$= 14{,}342\ \left(\frac{Nm3\ CO2}{d}\right) * \frac{50\ (\%)}{100} = 7{,}171\ \frac{Nm3\ CO2}{d}$$

$$[10]: H2\ demand\ AH2PD$$
$$= \frac{Weight\ CO2\ converted\ by\ H2\ injection\ * H2\ needed\ per\ CH4\ produces * molar\ weight\ H2}{molar\ weight\ CO2 * conversion\ efficiency\ H2\ to\ CH4\ (Bareau, 2020)}$$
$$= \frac{14.1 \frac{Tonne\ CO2}{d} * 4\ \left(\frac{H2}{CH4}\right) * 2\ (\frac{g\ H2}{mol})}{44\ \left(\frac{g\ CO2}{mol}\right) * \frac{90\ (\%)}{100}} = 2.8\ \frac{tonne\ H2}{d}$$

**Where:**

$$Weight\ CO2\ converted\ by\ H2\ injection$$
$$= \frac{CO2\ converted\ to\ CH4\ by\ H2\ injection\ *\ molar\ weight\ CO2 * 1000}{Molair\ volume\ ideal\ gas * 1000000}$$
$$= \frac{7{,}171\ \left(\frac{Nm3}{d}\right) * 44\ \left(\frac{g\ CO2}{mol}\right) * 1000\ (\frac{l}{NM3})}{22.414\ \left(\frac{l}{mol}\right) * 1{,}000{,}000\ (\frac{g}{tonne})} = 14.1\ \frac{tonne\ CO2}{d}$$

# Appendix 5. Allocation of the mass and energy flows

This appendix supports section 5.4 with the calculations behind the allocation. The most important calculations for the allocation can be found in this appendix.

## 5.1 Allocation for the baseline scenario

This section shows the most important calculations for the allocation of the baseline scenario. All calculations produce one of the results shown in Figure 24 in the report.

$$[\mathbf{1}]: Start\ allocation\ factor\ sludge\ line$$
$$= \frac{Internal\ COD\ input\ to\ AD\ from\ waterline}{External\ COD\ input\ to\ AD + Total\ COD\ input\ to\ AD\ from\ waterline}$$
$$= \frac{86.2\ (\frac{Tonne}{d})}{40.0\ \left(\frac{Tonne}{d}\right) + 86.2(\frac{Tonne}{d})} = 68.3\%\ (See\ start, figure\ 18)$$

$$[\mathbf{2}]: Start\ alocation\ factor\ waterline$$
$$= \frac{New\ wastewater\ to\ waterline + Internal\ COD\ input\ from\ return\ flow\ centrigue\ to\ waterline}{New\ wastewater\ to\ waterline + Total\ COD\ input\ from\ return\ flow\ centrifuge}$$
$$= \frac{91.4\ \left(\frac{Tonne}{d}\right) + 0.683(\%) * 17.7(\frac{Tonne}{d})}{91.4(\frac{Tonne}{d}) + 17.7(\frac{Tonne}{d})} = 94.9\%$$

$$[\mathbf{3}]: Loop\ 1, Internal\ COD\ input\ from\ the\ waterline\ to\ AD = \frac{Internal\ share\ waterline}{100} * COD\ production\ waterline = \frac{94.9\ (\%)}{100} * 86.2\ \left(\frac{Tonne}{d}\right) = 81.786\frac{Tonne}{d}$$

$$[\mathbf{4}]: Loop\ 1, External\ COD\ input\ from\ the\ waterline\ to\ AD$$
$$= \frac{(100 - Internal\ share\ waterline)}{100} * COD\ production\ waterline$$
$$= \frac{\big(100 - 94.9\ (\%)\big)}{100} * 86.2\ \left(\frac{Tonne}{d}\right) = 4.437\frac{Tonne}{d}$$

$$[\mathbf{5}]: Loop\ 1, allocation\ factor\ sludge\ line$$
$$= \frac{Internal\ COD\ input\ to\ AD\ from\ waterline}{External\ COD\ input\ to\ AD + Total\ COD\ input\ to\ AD\ from\ waterline}$$
$$= \frac{81.8\ (\frac{Tonne}{d})}{40.0\ \left(\frac{Tonne}{d}\right) + 86.2\ (\frac{Tonne}{d})} = 64.8\%\ (See\ loop\ 1, figure\ 24)$$

$$[\mathbf{6}]: Loop\ 1, allocation\ factor\ waterer\ line$$
$$= \frac{New\ wastewater\ to\ waterline + Internal\ COD\ input\ from\ return\ flow\ centrigue\ to\ waterline}{New\ wastewater\ to\ waterline + Total\ COD\ input\ from\ return\ flow\ centrifuge}$$
$$= \frac{91.4\ \left(\frac{Tonne}{d}\right) + 0.648(\%) * 17.7(\frac{Tonne}{d})}{91.4(\frac{Tonne}{d}) + 17.7(\frac{Tonne}{d})} = 94.3\%\ (See\ loop\ 1, figure\ 24)$$

## 5.2 Allocation for A-trap scenario

The return flow to the waterline for the A-trap scenario is calculated using manual interpolation with excel. First, the return flow is assumed to be the same as for the PST, which is 17.729 tonne COD per day. The Excel model is used to calculate the effect of the A-trap on this return flow by calculating the new ODS input towards the AD from the waterline. This new ODS input is calculated to be 98.034 Tonne/d. This value is a combination of the ODS input from the waterline (From the A-trap and AD) and the external ODS input towards the AD (the calculation can be found in formula 28 of the appendix).

At the baseline scenario, the total COD input towards the AD was 126.2 tonne COD /d (See Figure 23), which equals 88,872 tonne ODS/d. Since the total ODS input towards the AD increases in the A-trap scenario (towards 98.034 tonne ODS/d), the return flow of the centrifuge also increases towards 19.557 tonne/d (See Formula 7)

$$[\mathbf{7}]: First\ order\ iteration\ return\ flow\ centrifuge = \frac{New\ input\ AD\ (A - trap\ situation)}{old\ input\ AD\ (PST\ situation)} * Return\ flow\ centrifuge\ (PST\ situation) = \frac{99.034\ \left(\frac{tonne\ ODS}{d}\right)}{88.872\ \left(\frac{tonne\ ODS}{d}\right)} * 17.729 \left(\frac{tonne\ COD}{d}\right) = 19.557\ \left(\frac{tonne\ COD}{d}\right)$$

The increasing return flow increases the total; input to the AD towards 99.205 tonne ODS/d. This is caused by an increasing ODS output of the A-trap and the ST, which is due to the increasing return flow. The increasing ODS output from the waterline towards the AD increases the total ODS input to the AD, which also increases the return flow again. As can be seen in Table 31. iteration was used to calculate the final return flow of the centrifuge. The interpolation stopped at the fifth loop since the return flow remained constant at 3 digits.

**TABLE 31: ALLOCATION RETURN FLOW A-TRAP SCENARIO**

| | Return flow from the centrifuge towards the waterline (tonne COD/d) | Total ODS input from the waterline towards AD (tonne ODS/d) |
|---|---|---|
| **Start** | 17.729 | 98.034 |
| **Loop 1** | 19.557 [7] | 99.205 |
| **Loop 2** | 19.790 | 99.354 |
| **Loop 3** | 19.820 | 99.373 |
| **Loop 4** | 19.824 | 99.376 |
| **Loop 5** | **19.824** | |

The calculation of the allocation factors for the water- and sludge line for the A-trap scenario uses the same principles as shown in Appendix 5.1. Because of this, these calculations are not written out.