The Hague University of Applied Sciences
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# Development of the Anaerobic Digester at Loswal "De Bonnen"

Submitted By

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# Abstract

The Netherlands has a mission to use 16% of sustainable energy by 2023, and 100% of sustainable energy by 2050, thus making green energy to be the only source of energy in the future. Foundation Loswal "De Bonnen" has 17.5 hectares of raw land where they want to develop a digester. The aim of this paper is to find out whether is going to be feasible to develop a digester using the CHP (combined heat and power). Municipality of Hoek van Holland and Loswal "De Bonnen" can provide with 1180 kg/day of food waste, and WWTP Nieuwe Waterweg with 102.24 $m^3$/day of sewage sludge. It results in total 65.7 $m^3$/h of biogas produced by the digester, or 38.8 $m^3$/h of methane part. Digester has a cylindrical shape, with 13.7 m of dimeter, 12.9 m of height, and 1902 $m^3$ of total volume. Hydrogen sulphide ($H_2S$), water vapour ($H_2O$), and siloxanes are removed from biogas before it enters the CHP. Due to partial efficiency of the CHP, 192.7 kW of thermal power, and 134.9 kW of electrical power are generated. Based on the equipment cost of €1,273,158, the total capital investment (TCI) is €7,244,270. The payback period (PBP) is 58 years, which makes the development unfeasible. It is advised to look for alternative investments, such as €0.011 (1.1 cents) paid per every kilogram of organic waste treated by the digester.

# Contents

# 1. Introduction

The Netherlands has a mission to use 16% of sustainable energy by 2023, and 100% of sustainable energy by 2050, while the emissions of $CO_2$ have to be reduced by 80-95% by 2050 in comparison to 1990 (Government of the Netherlands, 2021). This is the challenge that has to be taken in order to prevent any further global problems related to global warming and massive pollutions caused by industries. That is why green energy comes so handy in tackling this issue, as it can stop both the environmental problems by using fewer fossil fuels, and also to provide households and businesses with enough of energy. The foundation Loswal “De Bonnen” has a similar idea in mind. They want to see whether it is going to be feasible to produce their own green energy by installing the digester that could theoretically do it on site.

The foundation Loswal “De Bonnen” has a raw land of 17.5 hectares located by Rijnpoort where they plan to build a sustainable business park. It is going to be a logistical centre for different companies, as well as the place to realize the sustainable methods of energy production such as digestion. The main goal will be to produce this energy and then to supply it, to: the industries working by the area of Loswal “De Bonnen”, the neighbourhoods, or even the national grid. Because it is still a challenge to produce green energy that could fully replace energy produced by fossil fuels, the idea of developing a digester at Loswal “De Bonnen” has to be studied.

A digester (i.e. anaerobic digester, biodigester) is a vessel where the living microorganisms consume organic (biodegradable) matter and produce methane gas as a product of their activity (Klinkner, 2014). This is facilitated by constant mixing of organic matter in the digester to allow bacteria to spread evenly (Ward et al., 2008). When methane is collected in the sealed environment like the one present in the digester, there appear opportunities of using this methane in the same way as if it was produced from natural gas obtained from the crust of the Earth. Namely, biogas produced in the digester can be treated first, to remove the impurities and so to increase the concentration of methane, and second, treated biogas can be processed by the engine of combined heat and power system (CHP) to generate heat and electricity (Kaparaju & Rintala, 2013). Purified biogas is combusted in the engine in the same way as natural gas would be, the only difference is that this gas would be produced in an environmentally friendly way.

In order to understand whether it is going to be realistic for Loswal “De Bonnen” to develop a digester on their land, the research question can be formulated in this way: “**How feasible is the development of a digester at Loswal “De Bonnen”, if the produced biogas is used to generate heat and electricity by the combined heat and power system (CHP)?**”. It should be understood from the research question that the feasibility parameter is measured by the amount of biogas produced, which is used as a fuel in the CHP to generate energy, that in return will pay back for the whole process starting from the moment when it is sold. The sub-questions which can help in guidance throughout the whole project are the following:

- What type of organic source can be used and what will be the location of it?
- How much of organic source can be obtained?
- How should the digester and the whole production process be designed?
- How much of heat and electricity can be produced, recycled and sold?
- How fast the production expenses will be recovered in terms of the payback period?
- What kind of solutions could improve the result?

It is therefore desired to reduce the payback period to as low as possible, so the process could become feasible and investment wise. As a rule of thumb, the payback period should not be longer than 20 years, because after the period of 20 years there could be invented a better option to produce green energy out of organic waste than it is with the anaerobic digester now. Additionally, the current technology of biogas production might be modified or completely replaced with the newer one that would require to rebuild the whole process from scratch again. This makes it important to keep the payback period within the 20-year period and not more.

# 2. Materials and methods

## 2.1 Sources, locations and amounts

It was first important to identify the location of Loswal "De Bonnen" on the map, and then to conduct an analysis of potential sources of organic waste that could be collected and delivered to Loswal "De Bonnen". These sources had to be located in a close proximity to Loswal "De Bonnen" in order to prevent any excesses of greenhouse gas (GHG) emissions caused by transportation. The WWTP Nieuwe Waterweg appeared to be the closest neighbour to Loswal "De Bonnen" that could offer to reuse the accumulations of sewage sludge of organic nature in the digester. The exact amounts of produced sewage sludge and other relating data were provided by Anna van den Bor-Vidolova, the process technologist at Waterboard of Delfland. Erik Bongaards, the water chain manager at Waterboard of Delfland, explained that sewage sludge had been transported from the WWTP Nieuwe Waterweg to the WWTP De Groote Lucht since 2021, because it was too expensive to maintain the digestion of sewage sludge on site.

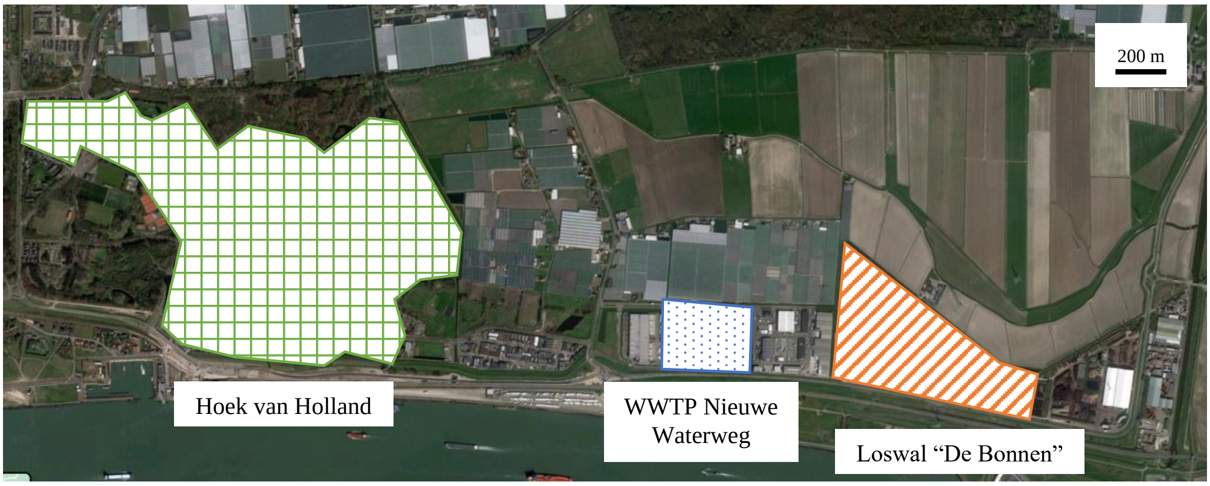


**Figure 1.** Map showing the location of Hoek van Holland, WWTP Nieuwe Waterweg, and Loswal "De Bonnen".

Another possible contributor of organic waste was considered to be the municipality of Hoek van Holland, where the inhabitants of Hoek van Holland were disposing solid waste with the partial fraction of organic matter such as of food waste. Using statistical online database such as Central Bureau of Statistics (https://www.cbs.nl/), it was possible to estimate the potential accumulation of organic waste per capita in Hoek van Holland that could be used as the secondary source for the digester. The part of food waste generated with time at Loswal "De Bonnen" was also estimated based on the population density in the Netherlands. The other locations, e.g. private companies, greenhouses, farms, were not considered as the reliable sources of organic waste because the access to them could only be achieved by direct negotiation with the owners, which was not conducted in the current research.

## 2.2 Process design

Methods of biogas production were researched on the basis of the modern biogas producers and their technologies. The closest example of a digester in the Netherlands working on a principle of sewage sludge and food waste digestion was the Orgaworld Greenmils anaerobic digester in Amsterdam that was using the technology of wet digestion, i.e. the concentration of dry matter was not higher than 10-15% (https://www.orgaworld.com/). The WWTP Harnaschpolder is the largest wastewater treatment plant in the Netherlands which was also using anaerobic digestion of sewage sludge in order to produce heat and electricity (https://delfluent-services.nl/). The WWTP Harnaschpolder served as an evidence to the digestion of sewage sludge on a large scale. Different technologies of biogas upgrading, i.e. methods of biogas purification, were adopted from such companies as DMT (https://www.dmt-cgs.com/) and Hitachi Zosen INOVA (https://www.hz-inova.com/). Both of these companies could describe major processing steps that were making biogas acceptable for the conversion to energy during the final stage by the CHP unit.

## 2.3 Energy

The conversion rate of biogas to energy using CHP system was estimated based on various literature resources. Every piece of equipment was analysed, and the power consumption and size of it were individually calculated in order to understand the amount of heat and electricity that could be recovered by recycling it back in the process. This gave a clear look of the amount of heat and electricity that were saved and that could be sold, and so Loswal "De Bonnen" could start generating profit. Additionally, heat loss in the digester was calculated for every month of the year, which showed the real amount of heat that had to be actually recycled back in the process.

## 2.4 Costs and feasibility

Equipment cost was the most important factor in the calculation of the total capital investment. Online equipment cost calculation tools (http://www.mhhe.com/; https://www.matche.com/) helped a lot in estimating the costs for the most of the equipment used in the process, while the others were based on scientific papers that had conducted an analysis of a certain type of equipment to generalize its price, such as for the digester and CHP unit. Based on the total equipment cost, the total capital investment was estimated using the method of Peters and Timmerhaus, which in return pointed out at the payback period, that could be otherwise interpreted as the feasibility parameter of the whole idea to develop the digester.

## 2.5 Investments

At the moment when the feasibility of the process was found, it was necessary to provide some data that could indicate on the reduction of the payback period and the consequent improvement of feasibility. It was chosen to suggest the investments that could be granted to Loswal "De Bonnen", which was executed by the calculation of the number of euros required to make the payback period be 20, 15, 10 and 5 years. Also, an additional investment was estimated by calculating the price of sludge transportation from the WWTP Nieuwe Waterweg to the WWTP De Groote Lucht, that could indicate a potential saving in favour of Loswal "De Bonnen" located in a closer proximity.

# 3. Results

## 3.1 Food waste

In 2019, there were 10 359 people who lived in Hoek van Holland, and their average production of organic waste, i.e. organic fraction of municipal solid waste (OFMSW), was 90 kg per person per day (Municipality of Rotterdam, 2019; Central Bureau of Statistics, 2019a). Based on the population density in the Netherlands, i.e. 513 inhabitants/km$^2$ (Central Bureau of Statistics, 2019b) and the area of Loswal “De Bonnen” (17.5 ha), there are expected to be 90 full-time inhabitants (employees) who will generate additional organic waste. Total organic waste from Hoek van Holland and Loswal “De Bonnen” is comprised of different organic materials, such as food waste, garden waste, textiles and paper, but only 45.8% of organic waste is food waste which is desirable for anaerobic digestion (Pecorini et al., 2017).

| Parameter | Unit | Hoek van Holland | Loswal "De Bonnen" |
|---|---|---|---|
| Population | inhabitants | 10 359 | 90 |
| Area | ha | n/a | 17.5 |
| Area | km$^2$ | n/a | 0.175 |
| Population density | inhabitants/km$^2$ | n/a | 513 |
| OFMSW | kg/person-year | 90 | 90 |
| Total OFMSW | kg/year | 932 310 | 8 079.8 |
| Total OFMSW | kg/day | 2 554.3 | 22.1 |
| FW/OFMSW | ratio | 45.8% | 45.8% |
| Total FW | kg/day | 1 169.9 | 10.1 |
| FW density | kg/m$^3$ | 513 | 513 |
| FW volume | m$^3$/day | 2.28 | 0.02 |
| TS/FW | ratio | 17.5% | 17.5% |
| TS | kgTS/day | 204.7 | 1.8 |
| VS/TS | ratio | 21.8% | 21.8% |
| Total VS | kgVS/day | 44.6 | 0.4 |
| BVS/VS | ratio | 40% | 40% |
| Total BVS | kgBVS/day | 17.9 | 0.2 |
| $CH_4$ yield ratio | m$^3$ $CH_4$/kgBVS | 0.20 | 0.20 |
| **$CH_4$ yield** | **m$^3$ $CH_4$/day** | **3.57** | **0.03** |

**Table 1.** Characteristics of food waste collected from Hoek van Holland and Loswal “De Bonnen” with total methane potential given in the end of the table.

Density of food waste is 513 kg/m$^3$ (Paritosh et al., 2018), so having found total OFMSW (2,554.3 and 22.1 kg/day) and FW (1,169.9 and 10.1 kg/day) in Hoek van Holland and Loswal “De Bonnen”, volume of FW is estimated to be 2.28 and 0.02 m$^3$/day, respectively. Dry solid concentration (DS) in FW, i.e. ratio of total solids (TS) per mass of food waste (FW), is 17.5% (Pecorini et al., 2017), so the number of total solids (TS) is 204.7 and 1.8 kgTS/day. Ratio of volatile solids (VS) to total solids (TS), i.e. the part of food waste that can be converted into gas, is 21.8% (Pecorini et al., 2017), therefore total volatile solids (VS) present in organic waste of both streams is 44.6 kg/day for Hoek van Holland, and 0.4 kg/day for Loswal “De Bonnen”. Ratio of biodegradable volatile solids (BVS) to volatile solids (VS), i.e. the part of food waste that can be directly consumed by bacteria in the anaerobic digester, is 40% (Zhen et al., 2017). Methane yield ratio for food waste is 0.20 m$^3$ $CH_4$/kgBVS (Xu et al., 2018), which is the volume of methane that is produced from 1 kilogram of biodegradable volatile solids. As a result, food waste collected from Hoek van Holland produces 3.57 m$^3$ $CH_4$/day, and 0.03 m$^3$ $CH_4$/day is produced from Loswal “De Bonnen”.

## 3.2 Sewage sludge

The wastewater treatment plant (WWTP) Nieuwe Waterweg produced a total amount of 102.24 m$^3$ of sewage sludge per day on average in 2019 (Bor-Vidolova, 2019), which was a combination of primary and secondary sludge, i.e. the types of sludge with slightly different characteristics. The concentration of dry solid (DS) material, i.e. the material opposite to water content, is estimated to be around 5.42%, based on dry solid (DS) concentration of primary (5.46%) and secondary (5.39%) sludge. Mass of dry solids (DS) alone was 2 631.3 kg/day for primary sludge, and 2 916.6 kg/day for secondary. Having identified these two characteristics and the dry solid concentration (DS), the total mass flow rate of sewage sludge resulted in 102 303.2 kg/day with the density of 1000.58 kg/m$^3$.

| **Parameter** | **Unit** | **WWTP Nieuwe Waterweg** | | |
|---|---|---|---|---|
| | | **Primary sludge** | **Secondary sludge** | **Total** |
| Volume | m³/year | 17 586 | 19 733 | 37 319 |
| Volume | m³/day | 48.18 | 54.06 | 102.24 |
| DS | ratio | 5.46% | 5.39% | 5.42% |
| Mass DS | kgDS/year | 960 427 | 1 064 549 | 2 024 976 |
| Mass DS | kgDS/day | 2 631.3 | 2 916.6 | 5 547.9 |
| Mass | kg/day | 48 192.4 | 54 110.8 | 102 303.2 |
| Density | kg/m³ | 1 000.24 | 1 000.88 | 1 000.58 |
| Biogas yield | m³ biogas/kgDS | n/a | n/a | 0.283 |
| Biogas yield | m³ biogas/day | n/a | n/a | 1 570.77 |
| $CH^4$/biogas | ratio | n/a | n/a | 59% |
| **$CH^4$ yield** | **m³ $CH^4$/day** | **n/a** | **n/a** | **926.76** |

**Table 2.** Characteristics of sewage sludge collected from the WWTP Nieuwe Waterweg with total methane potential given in the end of the table.

Based on the sewage sludge obtained specifically from the WWTP Nieuwe Waterweg, biogas yield is 0.283 m³ biogas/kgDS, which means that 283 litres of biogas are produced from 1 kilogram of dry solids (DS) of sewage sludge. The total biogas yield then is 1 570.77 m$^3$ of biogas produced daily. Ratio of methane ($CH_4$) in biogas produced by the WWTP Nieuwe Waterweg in 2019 was 59%, which gives 926.76 m$^3$ of pure methane produced per day.

## 3.3 Total feedstock

Sewage sludge from the WWTP Nieuwe Waterweg has the methane potential of 38.61 m$^3$ per hour, meaning that 38.61 m$^3$ of methane are likely to be produced when sewage sludge is exposed to bacteria in the digester. For food waste collected from Hoek van Holland, the methane potential is 0.1488 m$^3$ per hour, and 0.0013 m$^3$ per hour for food collected from Loswal "De Bonnen".

| **Location** | **Type** | **Mass** (kg/h) | **Volume** (m³/h) | **Density** (kg/m³) | **DS** (ratio) | **$CH_4$ yield** (m³/h) |
|---|---|---|---|---|---|---|
| WWTP Nieuwe Waterweg | Sewage sludge | 2 310.0 | 2.23 | 1 037 | 10.0% | 38.61 |
| Hoek van Holland | Food waste | 48.7 | 0.10 | 513 | 17.5% | 0.1488 |
| Loswal "De Bonnen" | Food waste | 0.4 | 0.042 | 513 | 17.5% | 0.0013 |
| (recycled in the process) | Water | 36.8 | 0.002 | 1 000 | n/a | n/a |
| **Total** | **Organic waste** | **2 396.0** | **2.365** | **1013** | **10.0%** | **38.8** |

**Table 3.** Characteristics and composition of total feedstock that enters anaerobic digester.

Total feedstock is consisted of sewage sludge, food waste, and water, which is used internally in the process as a recycled by-product. Final mass flow rate in the inlet stream of the digester is 2 396 kg/h, and the volumetric flow rate is 2.365 m$^3$/h. Density and dry solid concentration (DS) are 1013 kg/m$^3$ and 10%, respectively. Methane ($CH_4$) yield based on the sewage sludge and food waste is 38.8 m$^3$/h.

## 3.4 Digester

The type of the digester is a CSTR (continuous stirred-tank reactor), which is the most common choice for the digesters (Cheng, 2018). Digestion occurs under mesophilic conditions, i.e. a constant temperature of 37°C is kept in the digester (Baere & Mattheeuws, 2012). Total volume of organic waste that enters the digester is 56.8 m$^3$ a day. As the hydraulic retention time (HRT) is 30 days (Náthia-Neves et al., 2018), i.e. during this period of time organic waste is kept in the digester, the total volume of liquid that the digester processes within the 30 days period is 1 703 $m^3$.

| Digester parameter | Unit | Amount |
|---|---|---|
| Volume input | $m^3$/day | 56.8 |
| HRT | days | 30 |
| Liquid volume | $m^3$ | 1 703 |
| Diameter | m | 13.7 |
| Height | m | 12.9 |
| Real volume | $m^3$ | 1 902 |
| Liquid height | m | 11.6 |
| Gas space | ratio | 10.5% |

**Table 4.** Designing specifications of the digester.

The digester has a cylindrical shape, and a diameter of 13.7 m, and a height of 12.9 m, and the actual size of 1 902 $m^3$. The liquid inside of the digester fills it up to the height of 11.6 meters, leaving the remaining 10.5% of free space for the accumulation of biogas and for the prevention against any overflows (Kumar, 2012).

## 3.5 Biogas

Total volume of biogas produced in the digester is 65.7 $m^3$ per hour, which is based on 59% of methane being present in biogas (Bor-Vidolova, 2019). Around 3% of biogas are composed of water vapour, 0.2% of nitrogen, 0.2% of hydrogen sulphide and 0.01% of ammonia (Awe et al., 2017). The remaining part is the concentration of $CO_2$ which is 37.59%, together with the traces of siloxanes (Chen et al., 2015).

| Biogas component | Abbreviation | Ratio | Volume ($m^3$/h) |
|---|---|---|---|
| Methane | $CH_4$ | 59% | 38.76 |
| Carbon dioxide | $CO_2$ | 37.59% | 24.70 |
| Water vapour | $H_2O$ | 3% | 1.97 |
| Nitrogen | $N_2$ | 0.2% | 0.13 |
| Hydrogen sulphide | $H_2S$ | 0.2% | 0.13 |
| Ammonia | $NH_3$ | 0.01% | 0.01 |
| Siloxanes | n/a | traces | n/a |
| **Total** | **Biogas** | **100%** | **65.7** |

**Table 5.** Composition of biogas produced in the digester.

## 3.6 Process Flow Diagram (PFD)

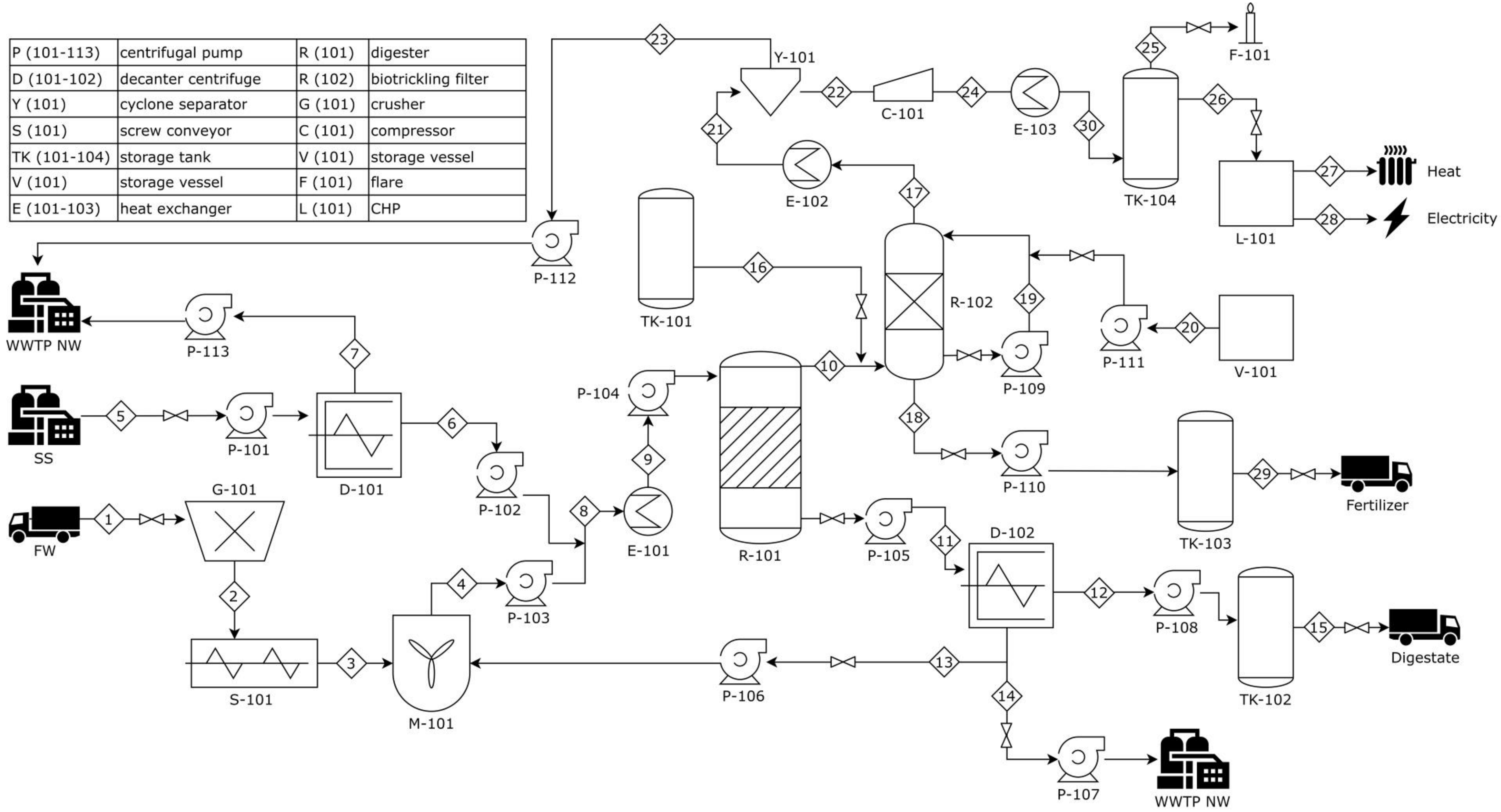


**Figure 2**. Process flow diagram of the process (streams 7, 14 & 23 and doubled pictogram of WWTP NW are separated for visualisation purposes; in reality, they are combined).

## 3.7 Process description

The municipal truck loaded with food waste that was collected from Hoek van Holland comes daily to Loswal "De Bonnen". Food waste from Hoek van Holland and Loswal "De Bonnen" is unloaded and grinded in the crusher (G-101) to reduce the size and so to improve the anaerobic digestion (Klinkner, 2014). It is considered that the truck discharges organic waste for 15 minutes. If necessary, the crushing machine can be additionally equipped with the tools to separate organic waste from the contaminants of other materials like metal, plastic, glass and fabric. Grinded food waste falls down by gravity in the screw conveyor (S-101) which transfers the material to the mixing tank (M-101). Recycled water and food waste are mixed together in the mixing tank (M-101) in order to decrease dry solid (DS) concentration of food waste from 17.5% to 10%.

Meanwhile, the mixture of primary and secondary sludge from the wastewater treatment plant (WWTP) Nieuwe Waterweg is centrifuged in the decanter centrifuge (D-101) until the concentration of dry solids (DS) is increased from 5.42% to 10%. Decanter centrifuge is considered to be located by the area of the WWTP to reduce power consumption of the pump (P-101) that would otherwise transfer higher volumes of sewage sludge to the biogas production site. Centrifuged water is sent back to the WWTP by means of the centrifugal pump (P-113).

Both streams (centrifuged sewage sludge and food waste) are pumped (P-102, P-103) further to the heat exchanger (E-101) where they are heated to 37°C. Heated organic waste enters the digester (R-101) where it is kept under the constant agitation for 30 days and under temperature of 37°C. Produced biogas goes to the biotrickling filter (R-102) where 95% of hydrogen sulphide ($H_2S$) is removed (Syed et al., 2006). Oxygen is constantly supplied to the biotrickling filter from the storage tank (TK-101) in order to oxidise sulphides to elemental sulphur and sulphate using Thiobacillus bacteria (Barbusinski & Kalemba, 2016). This tank (TK-101) is stored under pressure of 100 bar and is refilled with oxygen once in a month. Water and nutrients are continuously recycled in the biotrickling filter (R-102) by the centrifugal pump (P-109) by spraying them over the packed bed of growing bacteria, i.e. a layer to where bacteria are attached, that consume hydrogen sulphide (Rattanapan & Ounsaneha, 2011). Freshly supplied mixture of water and nutrients is provided to the biotrickling filter (R-102) from the storage vessel (V-101). The volume of the storage vessel (V-101) is designed to be refilled once in a year (365 days) and is assumed to supply 5% of fresh material. Fertilizer (Schieder et al., 2003), that comes out as a by-product from the biotrickling filter (R-102) is collected in the storage tank (TK-103), and is emptied once in a month by a truck.

Thickened by gravity sludge (digestate) accumulates at the bottom of the digester with time (Hanum et al., 2019), and is therefore sucked out by the centrifugal pump (P-105) to the decanter centrifuge (D-102). The concentration of dry matter of digestate is increased to 30%, and is collected after in the storage tank (TK-102). The storage tank (TK-102) is designed to be 30% filled every day, hence it can be emptied by a truck every 1-3 days. Centrifuged water from the decanter centrifuge (D-102) is partially recycled to the mixing tank (M-101), but most of it returns back to the WWTP Nieuwe Waterweg.

Biogas, purified from hydrogen sulphide, leaves the biotrickling filter (R-102) and enters heat exchanger (E-102), where it cools down from 37°C to 9°C (Hovland & Øi, 2018). Cooled biogas enters cyclone separator (Y-101) where all water together with the traces of siloxanes present in biogas condenses (Petersson & Wellinger, 2009; Rietema & Verver, 1961) and flows back to the WWTP Nieuwe Waterweg. Clean biogas is then compressed in the compressor (C-101) to 100 bar. Compression consequently increases temperature of biogas to 574°C, which is reduced to 50°C by cooling biogas in the heat exchanger (E-103). Compressed biogas is stored in the storage tank (TK-104), where it can be kept for up to 5 days if no biogas supply is needed. If the excesses of biogas are produced, biogas can be flared (F-101). Finally, biogas from the storage tank (TK-104) enters the CHP unit (L-101) where it is converted into heat and electricity.

## 3.8 Energy generation and heat requirement

The amount of produced biogas and its methane yield are considered to be similar for each month, because the supply of food waste and sewage sludge is estimated per annum, meaning that any monthly change would eventually be averaged to 930.36 $m^3$ of methane produced per day. A combined heat and power system (CHP) uses the gas engine, such as the combustion engine, to generate heat and electricity (Kaparaju & Rintala, 2013). Because the conversion rate of methane to energy by the CHP system is 35 800 kJ/$m^3$ (Liu et al., 2018), the total power produced is 385.5 kW (for a CHP operating full year, 365 days).

| **Month** | **Methane** | | **CHP** | | | **Feed** | **Digester** |
|---|---|---|---|---|---|---|---|
| | **$CH_4$ yield** ($m^3$/day) | **$CH_4$ heat value** (kJ/$m^3$) | **Total produced** (kW) | **Power** (kW) | **Heat** (kW) | **Preheating** (kW) | **Heat loss** (kW) |
| January | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.33 |
| February | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.40 |
| March | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.33 |
| April | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.19 |
| May | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.99 |
| June | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.78 |
| July | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.57 |
| August | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.51 |
| September | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.71 |
| October | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 1.99 |
| November | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.19 |
| December | 930.36 | 35,800 | 385.5 | 134.9 | 192.7 | 57.59 | 2.33 |

**Table 6.** Total production of thermal and electrical power by CHP, and heat requirement depending on the month in Hoek van Holland.

The efficiency of the CHP system is 85%, where 50% are responsible for the production of thermal power, i.e. heat, and the remaining 35% for the production of electrical power, i.e. electricity (Han et al., 2016). This results in production of 192.7 kW of thermal power, and 134.9 kW of electrical power, and the rest to be lost due to the partial efficiency of the CHP. Based on the in-depth analysis shown in tables in Appendix 1, total thermal power required for preheating of organic waste by the heat exchanger is 57.59 kW. However, an additional thermal power in the process is required to compensate for the heat loss that occurs in the digester, and which is dependent on the month of the year or more precisely on temperature of the surrounding and the wind speed. As a result, the highest demand of thermal power due to the heat loss of the digester happens in winter, with values of 2.33 – 2.40 kW, then spring, 1.99 – 2.33 kW, then autumn, 1.71 – 2.19 kW, and the smallest in summer, 1.51 – 1.78 kW.

## 3.9 Electricity requirement

A total of 57.637 kW of electrical power is used by all the equipment designed for the process. The most electricity consuming type of equipment is the agitator (mixing device) installed in the digester, which requires 19.3 kW of electrical power. After it, goes the compressor with 15.276 kW, that serves to compress biogas to 100 bar. Then, the decanter centrifuges which centrifuge organic sources to remove water, with the total consumption of 11.1 kW for D-101, and 9.8 kW for D-102.

| **Equipment** | **Number** | **Electrical power, kW** |
|---|---|---|
| Crusher | G-101 | 0.084 |
| Screw conveyor | S-101 | 0.010 |
| Mixing tank (agitator) | M-101 | 0.070 |
| Compressor | C-101 | 15.276 |
| Pump | P-101 | 0.024 |
| Pump | P-102 | 0.962 |
| Pump | P-103 | 0.00024 |
| Pump | P-104 | 0.129 |
| Pump | P-105 | 0.018 |
| Pump | P-106 | 0.00021 |
| Pump | P-107 | 0.822 |
| Pump | P-108 | 0.020 |
| Pump | P-109 | 0.004 |
| Pump | P-110 | omitted |
| Pump | P-111 | omitted |
| Pump | P-112 | omitted |
| Pump | P-113 | 0.018 |
| Heat exchanger (cooling) | E-102 | - 0.892 |
| Heat exchanger (cooling) | E-103 | - 10.542 |
| Digester (agitator) | R-101 | 19.300 |
| Decanter centrifuge | D-101 | 11.100 |
| Decanter centrifuge | D-102 | 9.800 |
| **Total** | **n/a** | **57.637** |

**Table 7.** Electrical power used by different equipment in the process.

Two heat exchangers, E-102 and E-103, do not consume any power but on opposite exchange and recycle it, because hot biogas is needed to be cooled by them. Therefore, water that is recycled in these heat exchangers takes 0.892 kW of thermal power from E-102 and 10.542 kW of thermal power from E-103, giving extra 11.434 kW of thermal power to the total amount of thermal power produced by the CHP. The least amount of electrical power is consumed by the crusher (G-101), 0.084 kW, mixing tank (M-101), 0.07 kW, screw conveyor (S-101), 0.01 kW, and the pumps (P-101 – P-113), 0.00021 – 0.962 kW, while the omitted results for the pumps P-110 – P-112 are due to the negligible volumetric flowrates processed.

## 3.10 Equipment cost

All major equipment that takes place in the production of biogas and further generation of energy has an estimated price of €1,273,158. Three central pieces of equipment, are: digester, biotrickling filter and CHP, that comprise almost €1M. For the digester, the influencing variable is its own size of 1 902 $m^3$, which makes the cost to be €548,623 (Jain, 2013). For the biotrickling filter, it is also the size which is 71 $m^3$ and the total cost of €223,984 (Peters et al., 2003). And for the CHP unit it is the amount of total energy generated which is 385.5 kW with the cost of €211,852 (Jain, 2013).

| **Equipment** | **Number** | **Equipment cost (EC)** € | **Operation and maintenance (O&M)** €/year |
|---|---|---|---|
| Digester (+ agitator) | R-101 | 548,623 | 38,404 |
| Biotrickling filter | R-102 | 223,984 | 7,483 |
| CHP (engine) | L-101 | 211,852 | 33,769 |
| Crusher | G-101 | 24,995 | n/a |
| Screw conveyor | S-101 | 13,194 | n/a |
| Mixing tank (+ agitator) | M-101 | 17,799 | n/a |
| Decanter centrifuge (sewage sludge) | D-101 | 49,325 | n/a |
| Decanter centrifuge (digestate) | D-102 | 45,741 | n/a |
| Cyclone separator | Y-101 | 2,958 | n/a |
| Storage tank | TK-101 | 3,945 | n/a |
| Storage tank | TK-102 | 24,425 | n/a |
| Storage tank | TK-103 | 7,136 | n/a |
| Storage tank | TK-104 | 31,726 | n/a |
| Storage vessel | V-101 | 9,817 | n/a |
| Heat exchanger (heating) | E-101 | 3,407 | n/a |
| Heat exchanger (cooling) | E-102 | 2,022 | n/a |
| Heat exchanger (cooling) | E-103 | 1,901 | n/a |
| Compressor | C-101 | 25,565 | n/a |
| Pump | P-101 | 1,682 | n/a |
| Pump | P-102 | 5,733 | n/a |
| Pump | P-103 | 1,664 | n/a |
| Pump | P-104 | 2,955 | n/a |
| Pump | P-105 | 1,545 | n/a |
| Pump | P-106 | 1,599 | n/a |
| Pump | P-107 | 5,442 | n/a |
| Pump | P-108 | 1,603 | n/a |
| Pump | P-109 | 968 | n/a |
| Pump | P-110 | negligible | n/a |
| Pump | P-111 | negligible | n/a |
| Pump | P-112 | negligible | n/a |
| Pump | P-113 | 1,553 | n/a |
| **Total** | **n/a** | **1,273,158** | **79,656** |

**Table 8.** Cost estimation of the major equipment in the process.

The cost for operation and maintenance (O&M) is estimated only for the digester, biotrickling filter and CHP, because they all three make the largest share of the total price of equipment, therefore O&M of the remaining equipment is neglected. The O&M of the digester is €38,404 per year, of the biotrickling filter is €7,483, and of the CHP is €33,769, so the total is €79,656 per year. Another considerable cost of equipment belongs to the decanter centrifuges, where D-101 has a cost of €49,325, and D-102 costs €45,741. Storage tanks vary from €3,945 to €31,726, where the price quickly increases as does the size of a storage tank, such as for the compressed biogas (TK-102), €24,425, and for the centrifuged digestate (TK-104), €31,726. The gas compressor C-101 reaches the price of €25,565, and a crusher G-101 of €24,995, which has a high price but which is used in reality only for 15 minutes every day at the moment when food waste is delivered. Storage vessel, screw conveyor and mixing tank cost €9,817, €13,194, and €17,799, respectively. And the pumps, cyclone separator and heat exchangers make the lowest costs in the range of €968 – 5,733.

## 3.11 Total cost

Total capital investment (TCI), i.e. the amount of money that is required for the realization of the whole process, is €7,244,270, which is based on the total cost of the major equipment of €1,273,158. Cost estimation is performed using Peters and Timmerhaus method (Couper, 2003). The direct plant costs is the type of costs which is spent once on things which do not require any additional expenses in the future, such as the equipment cost, buildings, land, piping etc., and which is €4,405,127.

| Cost item | Cost, € |
|---|---|
| Delivered equipment | 1,273,158 |
| Equipment installation labour | 598,384 |
| Instrumentation and controls | 229,168 |
| Piping | 840,284 |
| Electrical installations | 140,047 |
| Buildings | 229,168 |
| Yard improvements | 127,316 |
| Service facilities | 891,211 |
| Land | 76,389 |
| **Direct plant costs** | 4,405,127 |
| Engineering and supervision | 420,142 |
| Construction expenses | 521,995 |
| **Direct and indirect costs** | 5,347,264 |
| Contractor's fee | 267,363 |
| Contingency | 534,726 |
| **Fixed-capital investment (FCI)** | 6,149,354 |
| Working capital (WC) | 1,094,916 |
| **Total capital investment (TCI)** | 7,244,270 |

**Table 9.** Cost estimation of the whole process based on Peters and Timmerhaus method (Couper, 2003).

Indirect costs do not necessarily account for the money that are spent on the processing objects, but more for the expertise needed to achieve the end-goal. In the process, these are the costs for engineering, supervision, and construction expenses, making up €5,347, 264 together with the direct costs. Fixed capital investment (FCI) summarizes direct and indirect costs, but also adds contractor’s fees, i.e. financial benefit for the assigned company that will be building up the process, and the contingency factor, i.e. extra money saved for any deviations from the plan. Fixed capital investment (FCI) is €6,149,354. Finally, the working capital (WC) shows how much is needed to be paid for the cash flows directed to the every-day tasks like salaries and supplies, resulting in €1,094,916.

## 3.12 Feasibility

Out of 192.7 kW power of heat, and 134.9 kW power of electricity generated by the CHP system, and also 11.434 kW power of heat recycled by the heat exchangers E-102 and E-103, only 144.6 kW power of heat, and 77.3 kW power of electricity are saved. This gives the total of 221.8 kW power of energy saved after it has been recycled on the processing needs. The duration of the SDE++ subsidy program is 12 years, meaning that after that period no subsidy is provided (SDE++, 2020). SDE++ provides financial help only for a part of the year of 5 729 hours, leaving 3 031 hours non-subsidized based on the digester that functions whole year for 8 760 hours. Base amount of 0.044 €/kWh, and base energy price of 0.033 €/kWh, are the SDE++ values responsible for the total subsidy calculation. Electricity tariff in the Netherlands in 2020 was 0.156 €/kWh for households, and 0.095 €/kWh for businesses (GlobalPetrolPrices, 2020), and the heat tariff in 2021 is 25.51 €/GJ (ACM ConsuWijzer, 2021).

| Parameter | Unit | Amount |
|---|---|---|
| **Power produced by CHP** | | |
| Thermal | kW | 192.7 |
| Electrical | kW | 134.9 |
| **Power recycled by E-102 & E-103** | | |
| Thermal | kW | 11.434 |
| **Power savings** | | |
| Thermal, average | kW | 144.6 |
| Electrical | kW | 77.3 |
| Total | kW | 221.8 |
| **SDE++ subsidy** | | |
| Duration | years | 12 |
| Max. period | hours/year | 5,729 |
| Base amount | €/kWh | 0.044 |
| Base energy price | €/kWh | 0.033 |
| **Energy tariffs** | | |
| Electricity, to households | €/kWh | 0.156 |
| Electricity, to businesses | €/kWh | 0.095 |
| Heating | €/GJ | 25.51 |
| **Digester** | | |
| Working time | hours/year | 8,760 |
| Non-subsidized time | hours/year | 3,031 |
| **Product costs** | | |
| Manufacturing costs (O&M) | €/year | 79,656 |
| **Feasibility** | | |
| Heat sold, all | €/year | 116,297 |
| Electricity sold, all: | | |
| a. to households | €/year | 105,616 |
| b. to offices | €/year | 64,317 |
| Subsidy, SDE++ | €/year | 20,649 |
| Revenue, a | €/year | 221,913 |
| Gross profit, a | €/year | 142,257 |
| Corporate tax (GP < € 245,000) | ratio | 0.15 |
| Net profit, a | €/year | 120,918 |
| Payback period, a | years | 57.86 |

**Table 10.** Overview of the process in terms of feasibility with the payback back period given in the end of the table.

Considering total saved heat of 144.6 kW power being completely sold for €116,297 per year, and total saved electricity of 77.3 kW power for €105,616 to households (in order to generate the maximal benefit in comparison to businesses), the total revenue each year is €221,913. Because the manufacturing cost, i.e. operation and maintenance, is €79,656 per year, the gross profit produced is €142,257. The corporate tax in the Netherlands for 2021 is 15% due to the gross profit being lower than €245,000 (Government of the Netherlands, 2021), so the net profit, i.e. a sum after all deductions, is €120,918 per year. This results in the payback period (PBP) of 57.86 years, or 58 full years, i.e. the period of time needed to pay back for the total capital investment (TCI) of €7,244,270.

## 3.13 Payback period

During the first 12 years, the cash flow is higher than during the further years because the governmental subsidy program SDE++ is only available for 12 years. Therefore, until the 12$^{th}$ year, the cash flow is €141,568 per year, with the total balance of €1,698,812 generated within 12 years. After that period, 23.45% of the total capital investment (TCI) are covered.

| Period | Cash flow per year, € | Balance, € | Balance, % |
|---|---|---|---|
| Years 1-12 | 141,568 | 1,698,812 | 23.45 |
| Years 12-58 | 120,918 | 7,261,047 | 100.23 |

**Table 11.** Difference in cash flows for the first 12 years and for the 12-58 years period.

During the years from 12 to 58, the cash flow is based only on the net profit of €120,918. After 58 years, the balance of €7,261,047 is accumulated (in contrast to €7,244,270 of TCI required), which ends up in the total balance of 100.23% covered.

## 3.14 Investment

Payback period (PBP) can be reduced up to 20 years and less if a specific party or a group of parties would share a seven-figure number of euros at once, or a smaller amount but then consistently. For example, in order to reduce the payback period (PBP) from 58 to 20 years, an investment of €4,578,113 can be made, so then the rest of the payback would only depend on the accumulation of the net profit and the subsidy SDE++. Similarly, the government and the WWTP Nieuwe Waterweg can make a contribution of €0.011 (1.1 cents) per every kilogram of organic waste, i.e. sewage sludge or food waste, that has been processed and reused in the digester.

| **Payback period,** years | **Investment,** € | **Investment,** €/kgOW |
|---|---|---|
| 5 | 6,536,432 | 0.063 |
| 10 | 5,828,594 | 0.028 |
| 15 | 5,182,704 | 0.017 |
| 20 | 4,578,113 | 0.011 |

**Table 12.** Reduced payback period with the alternative investments.

If the payback period (PBP) is desired to be reduced to 5, 10 or 15 years, then the one-time investment and the consistent investment will get bigger as long as the PBP becomes smaller. For example, the one-time investment for the PBP of 15, 10, and 5 years is going to be €5,182,704, €5,828,594, and €6,536,432, respectively. However, if the consistent type of an investment is preferred, then for the same payback periods the price for reusing the organic waste is going to be €0.017 (1.7 cents), €0.028 (2.8 cents), or €0.063 (6.3 cents), respectively.

## 3.15 Sludge transportation

The WWTP Nieuwe Waterweg is currently transporting centrifuged sludge from Hoek van Holland to Vlaardingen to the WWTP De Groote Lucht (Bongaards, 2021). If sewage sludge is centrifuged to a 30% dry solid (DS) concentration, its total mass flowrate is 18 482.7 kg/day, or 16.515 $m^3$/day (16 515 litres per day). The truck in this scenario needs to pick up this sludge only once per day, if the volume capacity of the truck is at least 16 515 litres. The distance between the WWTP Nieuwe Waterweg and the WWTP De Groote Lucht is around 17.2 km, which the truck can pass in 24 minutes if the average speed of the truck is 43 km/h. Fuel consumption of the truck is considered to be 28.6 litres per 100 km (BudgetDirect, 2020), fuel price for 95 RON (research octane number) is 1.774 €/L (GlobalPetrolPrices, 2021), and the driver's wage is around €12.5 per hour based on the average wages found on the job searching platform (https://nl.indeed.com/).

| Parameter | Unit | Amount |
|---|---|---|
| **Sewage sludge** | | |
| Mass | kg/day | 18 482.7 |
| Volume | $m^3$/day | 16.515 |
| **Truck** | | |
| Fuel consumption | L/100 km | 28.6 |
| Distance | km | 17.2 |
| Fuel price, 95 RON | €/L | 1.774 |
| **Driver** | | |
| Wage | €/h | 12.5 |
| Time | min | 24 |
| **Transportation** | | |
| Fuel cost | €/day | 8.73 |
| Driver's salary | €/day | 5.00 |
| Total cost | €/day | 13.73 |
| Total cost | €/year | 5,011 |
| Total cost | €/20 years | 100,220 |

**Table 13.** Characteristics of sludge transportation by the WWTP Nieuwe Waterweg.

As a result, the fuel cost is 8.73 €/day, the driver's salary is 5 €/day, and that makes the total cost for the WWTP Nieuwe Waterweg to transport the sewage sludge to be 13.73 €/day, or 5,011 €/year, or 100,220 €/20 years. These are the estimated prices that the WWTP Nieuwe Waterweg has to pay nowadays, and which can be instead contributed to Loswal "De Bonnen", which can produce green energy out of it in the sustainable way with no pollution to the environment, that is caused by the transportation of sewage sludge using the trucks.

# 4. Discussion

## 4.1 Feedstock

When comparing the streams of food waste and sewage sludge, it can be seen that the amount of sewage sludge strongly dominates over the food waste. Around 98.86% of total mass flowrate that is collected for digestion is attributed to sewage sludge from the WWTP Nieuwe Waterweg, in contrast to 1.14% for food waste. And when the same is compared for the production of methane, then the effect becomes even stronger, with 99.61% of methane produced from sewage sludge, leaving only 0.39% of methane produced from food waste that was collected from the municipality of Hoek van Holland and the area of Loswal "De Bonnen".

| Type | Mass (kg/day) | Percentage | Volume of methane ($m^3$ $CH_4$/day) | Percentage |
|---|---|---|---|---|
| Food waste | 1180 | 1.14% | 3.6 | 0.39% |
| Sewage sludge | 102 303.2 | 98.86% | 926.76 | 99.61% |
| **Total** | **103 483.2** | **100%** | **930.36** | **100%** |

**Table 14**. Characteristics of food waste and sewage sludge obtained on the daily basis.

With that it can be said, that the designed process is almost completely based on the digestion of sewage sludge, making the idea to develop a digester more applicable to the area of the WWTP Nieuwe Waterweg than to Loswal "De Bonnen". Transferring 98.86 wt%, i.e. percentage by weight, to Loswal "De Bonnen" requires more investments than if the digester was installed at the WWTP, because in the latter case there is no need to build a sewage sludge pipe anymore between the two locations, a pump, and also more free space would be left at Loswal "De Bonnen" which could be used for other purposes. Additionally, as provided by Erik Bongaards, the water chain manager at Water Board of Delfland, the WWTP Nieuwe Waterweg used to have a digester until 2021, meaning that there is enough of available space at their location to develop the digester and the whole purification system.

## 4.2 Digester

Legislation does not allow the height of any buildings to be higher than 15 meters at Loswal "De Bonnen". Although, the current height of the digester is 12.9 m and diameter is 13.7 m, there is a possibility to increase both the height and diameter to 15 m in order to increase the size of the digester (as a rule of thumb, ratio of height to diameter is preferred to be equal to 1). This means, that in case the capacity of the digester is desired to be increased because more streams of organic waste become available, this could be achieved by simply redesigning digester's diameter and height. Current size of the digester is 1 902 $m^3$, so the maximal size would be when the height and diameter are both around 15 m giving the total volume of 2 651 $m^3$, or 2 372 $m^3$ for just the volume of liquid flow of organic waste. In other words, the size of the digester can be increased by extra 39% if required.

## 4.3 Biogas

The biggest concern about the composition of biogas is to look for the components that have to be removed when biogas is produced in the digester. If the origins of these components are not tracked, then they can easily damage the equipment that is processing biogas. For example, siloxanes can cause gas engine problems, while water can condensate in the pipes and provoke corrosion (Petersson & Wellinger, 2009); and hydrogen sulphide is extremely corrosive to any type of metal in general (Awe et al., 2017). That is why, before biogas is sent to the CHP, it has to be treated in the sequence from most hazardous to the least, i.e. starting with the removal of hydrogen sulphide, and ending with the removal of water and siloxanes. Other impurities in biogas, such as carbon dioxide, nitrogen and ammonia are acceptable and are not as damaging to the CHP. However, the removal of carbon dioxide ($CO_2$) is desirable as it increases the concentration of methane ($CH_4$) making biogas be a better fuel in terms of its energy potential per volume of biogas (Carnevale & Lombardi, 2015). But in that case an extra unit for $CO_2$ removal would need to be installed. This would result in the larger total capital investment and payback period, as purifying biogas from $CO_2$ is not necessary until it is used in the CHP system.

## 4.4 Production process

Biogas production process is designed to produce biogas continuously whole year, but only if a supply of sewage sludge and food waste is maintained. Even though food waste is considered to be delivered every day, it cannot be added in the process on the hourly basis, because it is considered that the daily supply of 1180 kg of food waste is discharged into the crushing machine (G-101) within 15 minutes once it has been delivered by a truck. Therefore, the crushing machine (G-101) works only 15 minutes per day together with the mixing tank (M-101), and the rest of the day is completely dependent on the stream of sewage sludge.

## 4.5 By-products

There are at least two by-products in the process that have to be dealt with. The first one is centrifuged digestate. This cannot be used as a fertilizer due to the EU (European Union) law that prohibits reuse of sewage sludge in agriculture when sludge is not treated (Council Directive 86/278/EEC, 1986). This means that the only way to reuse digestate is either by recycling it again in the process or by sending it to incineration plant. Recycling can only be beneficial if digestate has not been fully digested by the bacteria. In this case, digestate can be pumped back to the digester first before it is centrifuged, however after centrifugation it is anyway sent to incineration plant. The second by-product is a fertilizer. It is produced as a result of biotrickling filtration. The main composition of this fertilizer is elemental sulphur, sulphate and water. It can be recycled by delivering it to any of the nearby greenhouses and farms where an additional fertilizer is needed.

## 4.6 Energy

Heat loss in the digester does not vary much within the year (min. 1.51 kW; max. 2.40 kW), because of the expanded polystyrene (EPS) insulation material from the both sides of the digester, and the concrete wall. This makes the process more effective, as it results in more thermal power saved and sold.

## 4.7 Process realities

Payback period of 58 years suggests, first, that methane potential of sewage sludge (as the main contributor of organic waste) is low, of course, based only on the rate of methane produced specifically by Thiobacillus bacteria who are the core reason of anaerobic digestion. This means, that anaerobic digestion alone is not sufficient to produce all potential methane from organic waste that is fed to the digester. And second, the process itself requires much energy to maintain the work of equipment and cover the needs for heating. With that said, the amount of energy generated by the CHP unit is limited and strongly bounded to the amount of methane produced. Any process optimizations could theoretically reduce the payback period either by improving the digestion of sewage sludge or food waste, or by reducing the requirements of thermal and electrical power by the process. Both of these trigger points are still not going to reduce the payback period from 58 years to somewhat acceptable 20 years, because the difference is too large for that.

This is why the chosen technology of anaerobic digestion has to be questioned instead, which in theory cannot provide with anything else than wet (DS < 16%) or dry (DS = 22 – 40%) digestion (Alastair et al., 2008); one stage (1 digester) or two stage (2 digesters) (Gerardi, 2003); mesophilic (37°C) or thermophilic (55°C) (Wang et al., 2007); or type of a reactor, CSTR (continuous stirred-tank reactor) or PFR (plug flow reactor). Any of the above mentioned design choices would not produce significantly more biogas, because sewage sludge when processed using the technology of anaerobic digestion lacks in biodegradability, i.e. a part of sewage sludge that could be digested by the bacteria to produce methane (Yucheng & Pawłowski, 2012), while the cost of the project can greatly increase.

# 5. Conclusion

The development of a digester at Loswal “De Bonnen” is not feasible, because it only relies on the generation of heat and electricity by the CHP. It takes 58 years to pay back for the project, and it is therefore necessary to search for alternative solutions in order to make anaerobic digestion feasible. One option is to require contributions from the government, WWTP Nieuwe Waterweg, water board etc., such as the price to be paid for every kilogram of organic waste digested at Loswal “De Bonnen”. In this case, the price of 1.1 cents per kilogram of organic waste is sufficient to reduce the payback period to 20 years. Another option, is to use one-time investment, i.e. grant, of €4,578,113 to reduce the PBP to 20 years. Otherwise, a contribution from the WWTP for sludge transportation of €5,011 per year will not be significant to cover the total capital investment of €7,244,270.

# Recommendations

## By-products

Around 13.8 tons of digested material (digestate) is eventually transferred to incineration plant. There, it releases more energy and so closes a recycling loop. Therefore, it is worth considering that the total amount of energy generated from organic waste becomes complete only at the incineration plant. And this suggests to think about the opportunities of applying a technology of incineration at Loswal "De Bonnen", or at least gaining more profit based on the amount of energy produced at the incineration plant from 13.8 tons of digestate. In addition, a fertilizer produced as a by-product of anaerobic digestion can be researched more in order to better identify all potential clients of it, and then to estimate revenue from selling or reusing 46.68 kg/day of fertilizer. The new research can study the feasibility of reusing the digested organic waste (sewage sludge, food waste) by finding out the technologies that could generate more energy or revenue (in case it is a new product) out of it.

## Digestion type

This research has covered one method of anerobic digestion (CSTR type, mesophilic conditions, one stage digester, wet digestion with DS = 10%), therefore other methods has to be studied as well in order to be able to compare them and to identify the most feasible one. Based on the data provided in this report, it will not be important anymore to identify organic streams and their amounts, type of equipment to be used etc. but only to conduct the necessary calculations for the equipment (power, cost, size etc.).

## Lab experiments

Obtained data regarding the biodegradability of food waste is theoretical and therefore it is suggested to conduct the lab experiment to see how much of biogas (and methane in there) can actually be produced. As an example, the regular food waste generated by the Dutch households can be used in these experiments. And as an analogue of a digester, a small-scale digester of a size of a bottle can be set up in the laboratory. Exploring the same for sewage sludge can be also effective, although the data provided by the WWTP Nieuwe Waterweg regarding their production results is already very reliable as it is based on the records from the past.

## Purification

In the process, biogas is treated only from the components that can damage the equipment. However, biogas can be upgraded even further by purging carbon dioxide, and so considerably increasing the concentration of methane. This will make biogas acceptable for the injection in the national gas pipeline system and producing revenue already based on a different business model. Because the new unit of equipment responsible for the removal of carbon dioxide will add extra expenses to the total capital investment, it is expected that the revenue generated from selling purified biogas to the national pipeline system has to be much higher than the current selling price for biogas. First, in order to be able to greatly reduce the payback period from 58 years to at least 20. And second, in order to compensate for the extra expenses caused by the carbon dioxide removal equipment that will additionally increase the payback period.

## Innovative solutions

Instead of using the CHP, biogas can be used as a fuel for vehicles. It has to be studied, but either biogas might be used directly as a fuel without additional treatments from carbon dioxide, either only after the removal of carbon dioxide. The examples can include trucks, boats, cars, or even as a separate product for devices that might use biogas in their systems, such as the compressed bottles of biogas for different ignition related uses etc. In this case, biogas can be also provided to the bakery working nearby, or can be used for the buses, such as municipal buses, that could be driven fully on biogas. Again, the amounts of biogas and selling prices are the crucial parts for achieving a sustainable and profitable model.

## Investments

More programs have to be discovered that could financially contribute to the idea of development of a digester at Loswal “De Bonnen”. This can be anything from subsidies such as SDE++ used in the report, to grants, loans, etc. One example is the Energy Investment Allowance (EIA) that works as a government tax scheme and helps in covering the expenses on equipment used for green energy. Another idea could be related to a cooperation between Loswal “De Bonnen” and the greenhouses. Because biogas is rich in carbon dioxide which is used in greenhouses, the greenhouses could be interested to use biogas, or to invest in the removal of carbon dioxide with the idea to use it for their own needs.

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# Appendix 1. Heat

| Preheating parameter | Unit | Amount |
|---|---|---|
| **Feed** | | |
| Temperature [1] | ˚C | 16.3 |
| Mass flowrate | kg/day | 57 504.0 |
| Specific heat [2] | J/kg ˚C | 4 180 |
| **Heat exchanger** | | |
| Temperature | ˚C | 37.0 |
| **Final** | | |
| ΔTemperature | ˚C | 20.7 |
| **Heat requirement** | **kW** | **57.6** |

**Table 15.** Thermal power used for preheating the feedstock by the heat exchanger E-101.

| Month | Total heat loss (kW) |
|---|---|
| January | 2.33 |
| February | 2.40 |
| March | 2.33 |
| April | 2.19 |
| May | 1.99 |
| June | 1.78 |
| July | 1.57 |
| August | 1.51 |
| September | 1.71 |
| October | 1.99 |
| November | 2.19 |
| December | 2.33 |
| **Average** | **2.03** |

**Table 16.** Heat loss in the digester depending on the month.

| Month | Heat needed (kW) | Heat saved (kW) |
|---|---|---|
| January | 59.9 | 132.8 |
| February | 60.0 | 132.8 |
| March | 59.9 | 132.8 |
| April | 59.8 | 133.0 |
| May | 59.6 | 133.2 |
| June | 59.4 | 133.4 |
| July | 59.2 | 133.6 |
| August | 59.1 | 133.6 |
| September | 59.3 | 133.4 |
| October | 59.6 | 133.2 |
| November | 59.8 | 133.0 |
| December | 59.9 | 132.8 |
| **Average** | **59.6** | **133.1** |

**Table 17.** Demand of heat for the process and heat savings.

| Month | Average | | Digester | Air | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Wind speed** (m/s) | **Temperature (low)** (˚C) | **Diameter** (m) | **Density** (kg/m³) | **Viscosity** (kg/m s) | **Conductivity** (W/m K) | **Prandtl number** | **Reynolds number** | **Nusselt number** | **Convective coefficient** |
| January | 7.5 | 3 | 13.7 | 1.279 | 1.738E-05 | 0.0243 | 0.71910 | 7,563,024 | 6,418 | 11.386 |
| February | 7.0 | 2 | 13.7 | 1.284 | 1.733E-05 | 0.0242 | 0.71932 | 7,104,237 | 6,105 | 10.797 |
| March | 6.4 | 3 | 13.7 | 1.279 | 1.738E-05 | 0.0243 | 0.71910 | 6,453,781 | 5,653 | 10.029 |
| April | 5.9 | 5 | 13.7 | 1.270 | 1.748E-05 | 0.0245 | 0.71866 | 5,872,870 | 5,241 | 9.357 |
| May | 5.3 | 8 | 13.7 | 1.256 | 1.763E-05 | 0.0247 | 0.71802 | 5,175,600 | 4,735 | 8.533 |
| June | 5.0 | 11 | 13.7 | 1.243 | 1.777E-05 | 0.0249 | 0.71739 | 4,791,261 | 4,450 | 8.094 |
| July | 5.0 | 14 | 13.7 | 1.230 | 1.792E-05 | 0.0251 | 0.71677 | 4,702,780 | 4,383 | 8.044 |
| August | 5.5 | 15 | 13.7 | 1.226 | 1.797E-05 | 0.0252 | 0.71657 | 5,140,913 | 4,706 | 8.663 |
| September | 5.9 | 12 | 13.7 | 1.239 | 1.782E-05 | 0.0250 | 0.71718 | 5,618,499 | 5,054 | 9.221 |
| October | 6.7 | 8 | 13.7 | 1.256 | 1.763E-05 | 0.0247 | 0.71802 | 6,542,739 | 5,712 | 10.293 |
| November | 6.8 | 5 | 13.7 | 1.270 | 1.748E-05 | 0.0245 | 0.71866 | 6,768,731 | 5,871 | 10.482 |
| December | 7.5 | 3 | 13.7 | 1.279 | 1.738E-05 | 0.0243 | 0.71910 | 7,563,024 | 6,418 | 11.386 |

**Table 18.** Air characteristics (MHTL, 1997) in Loswal "De Bonnen" with the average wind speed (Weather Spark, 2016) for Hoek van Holland and the average temperature (low) for Rotterdam (Climate Data, 2018).

| Month | Average | Air | Digester | | | | | | Value | Insulation | Material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Temperature (low)** (˚C) | **Convective coefficient** (W/m² K) | **Convective coefficient** (W/m² K) | **Temperature** (˚C) | **Diameter** (m) | **Radius** (m) | **Height** (m) | **Volume** (m³) | **ΔTemperature** (˚C) | **Conductivity, EPS** (W/m K) | **Conductivity, concrete** (W/m K) |
| January | 3 | 11.386 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 34 | 0.035 | 0.8 |
| February | 2 | 10.797 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 35 | 0.035 | 0.8 |
| March | 3 | 10.029 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 34 | 0.035 | 0.8 |
| April | 5 | 9.357 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 32 | 0.035 | 0.8 |
| May | 8 | 8.533 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 29 | 0.035 | 0.8 |
| June | 11 | 8.094 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 26 | 0.035 | 0.8 |
| July | 14 | 8.044 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 23 | 0.035 | 0.8 |
| August | 15 | 8.663 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 22 | 0.035 | 0.8 |
| September | 12 | 9.221 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 25 | 0.035 | 0.8 |
| October | 8 | 10.293 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 29 | 0.035 | 0.8 |
| November | 5 | 10.482 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 32 | 0.035 | 0.8 |
| December | 3 | 11.386 | 1,000 | 37 | 13.7 | 6.9 | 12.9 | 1,902 | 34 | 0.035 | 0.8 |

**Table 19.** Air characteristics in Loswal "De Bonnen". Parameters of the digester such as of insulation material EPS (expanded polystyrene) (Nuclear Power, 2021) and concrete (GreenSpec, 2021).

| Walls | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Radius 2** (m) | **Radius 3** (m) | **Radius 4** (m) | **Resistance conv. in.** (K/W) | **Resistance conv. out.** (K/W) | **Resistance cond. 1** (K/W) | **Resistance cond. 2** (K/W) | **Resistance cond. 3** (K/W) | **Resistance total** (K/W) | **Heat loss** (kW) |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.426E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.282E-02 | 1.49 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.504E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.283E-02 | 1.53 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.619E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.284E-02 | 1.49 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.735E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.285E-02 | 1.40 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.902E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.287E-02 | 1.27 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 2.006E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.288E-02 | 1.14 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 2.018E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.288E-02 | 1.01 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.874E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.286E-02 | 0.96 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.761E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.285E-02 | 1.09 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.577E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.283E-02 | 1.27 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.549E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.283E-02 | 1.40 |
| 7.1 | 7.4 | 7.6 | 1.801E-06 | 1.426E-04 | 1.264E-02 | 6.382E-04 | 9.401E-03 | 2.282E-02 | 1.49 |

**Table 20.** Characteristics of the walls of the digester with the total heat loss calculated.

| Ceiling, Floor | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Distance 1** (m) | **Distance 2** (m) | **Distance 3** (m) | **Resistance conv. in.** (K/W) | **Resistance conv. out.** (K/W) | **Resistance cond. 1** (K/W) | **Resistance cond. 2** (K/W) | **Resistance cond. 3** (K/W) | **Resistance total** (K/W) | **Heat loss** (kW) |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 5.96E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.07E-02 | 0.42 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 6.28E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.07E-02 | 0.43 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 6.76E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.08E-02 | 0.42 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 7.25E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.08E-02 | 0.40 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 7.95E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.09E-02 | 0.36 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 8.38E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.09E-02 | 0.32 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 8.43E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.09E-02 | 0.28 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 7.83E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.09E-02 | 0.27 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 7.36E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.08E-02 | 0.31 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 6.59E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.07E-02 | 0.36 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 6.47E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.07E-02 | 0.40 |
| 0.2 | 0.3 | 0.2 | 6.78E-06 | 5.96E-04 | 3.88E-02 | 2.54E-03 | 3.88E-02 | 8.07E-02 | 0.42 |

**Table 21.** Characteristics of the ceiling and floor of the digester with the total heat loss calculated (floor and ceiling are considered the same).

# Appendix 2. Mass balance

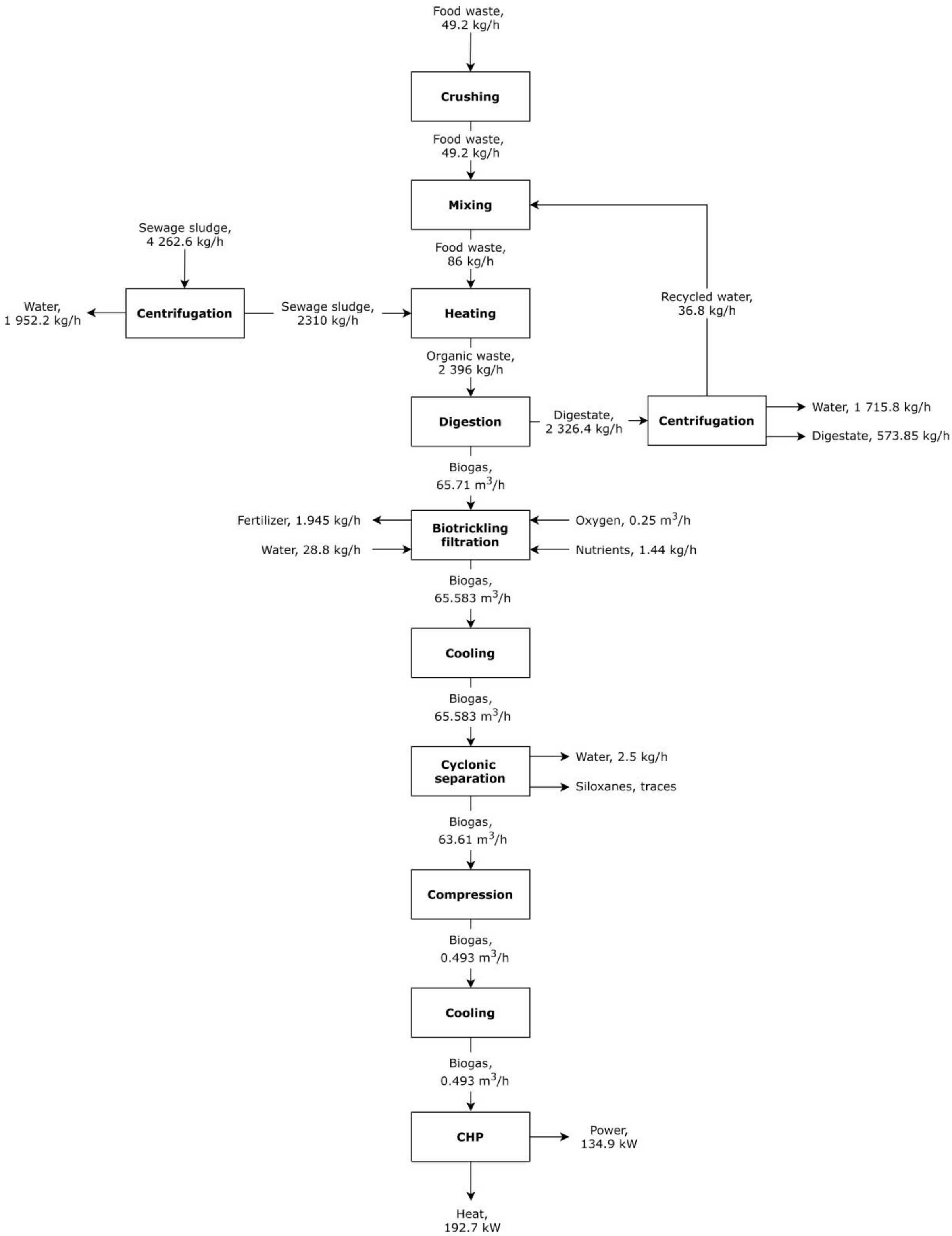


**Figure 3**. Mass balance of the process.

# Appendix 3. Streams

| Stream | Type | Mass (kg/h) | Volume ($m^3/h$) | Density ($kg/m^3$) | DS (%) |
|---|---|---|---|---|---|
| 1, 2, 3 | Food waste (crushed) | 49.2 | 0.096 | 513 | 17.5 |
| 4 | Food waste (mixed with water) | 86 | 0.1368 | 628.7 | 10 |
| 5 | Sewage sludge (primary and secondary) | 4 262.6 | 4.26 | 1000.58 | 5.42 |
| 6 | Sewage sludge (dewatered) | 2310 | 2.228 | 1037 | 10 |
| 7 | Water | 1 952.2 | 1.952 | 1000 | n/a |
| 8, 9 | Sewage sludge and food waste (mixed and preheated) | 2 396 | 2.365 | 1013.2 | 10 |
| 10 | Biogas | 69.6 | 65.71 | 1.059 | n/a |
| 11 | Digestate | 2 326.4 | 2.265 | 1027 | 7.4 |
| 12, 15 | Digestate (dewatered) | 573.85 | 0.513 | 1119 | 30 |
| 13 | Water | 36.8 | 0.037 | 1000 | n/a |
| 14 | Water | 1 715.8 | 1.716 | 1000 | n/a |
| 16 | Oxygen | 0.357 | 0.25 | 1.429 | n/a |
| 17, 21 | Biogas (purified from $H_2S$) | 69.452 | 65.583 | 1.059 | n/a |
| 18, 29 | Fertilizer | 1.945 | ≈ 0.002 | ≈ 1000 | n/a |
| 19 | Water and nutrients (recycled) | 28.8 | ≈ 0.029 | ≈ 1000 | n/a |
| 20 | Water and nutrients (added) | 1.44 | ≈ 0.001 | ≈ 1000 | n/a |
| 22, 24, 26, 30 | Biogas (purified from water) | 67.36 | 63.61 | 1.059 | n/a |
| 23 | Water | 2.5 | 0.0025 | 1000 | n/a |
| 25 | Biogas (to flare) | n/a | n/a | 1.059 | n/a |
| 27 | Thermal power | n/a | n/a | n/a | n/a |
| 28 | Electrical power | n/a | n/a | n/a | n/a |

**Table 22.** Characteristics of the streams of the biogas production process in addition to the process flow diagram (PFD).

# Appendix 4. Equipment sizes

**Table 23.** Characteristics of the equipment used in the process.

| Equipment | Number | Parameter | Unit | Amount |
|---|---|---|---|---|
| Digestion agitator | R-101 | RPM | - | 25 |
| | | Diameter | m | 3.81 |
| | | Length | m | 7.7 |
| | | $N_p = K_T$ | - | 0.32 |
| Mixing tank | M-101 | Volume | $m^3$ | 3.9 |
| | | Diameter | m | 1.7 |
| | | Height | m | 1.7 |
| | | Time | min | 15 |
| Cyclone separator | Y-101 | Diameter | m | 0.202 |
| Pump | P-101 | Pipe L | m | 15 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.032 |
| | | Coeff.min. | - | 1.07 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-102 | Pipe L | m | 820 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.023 |
| | | Coeff.min. | - | 0.9 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-103 | Pipe L | m | 15 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.06 |
| | | Coeff.min. | - | 0.9 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-104 | Pipe L | m | 15 |
| | | Height | m | 12.9 |
| | | Pipe D | m | 0.024 |
| | | Coeff.min. | - | 0.6 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-105 | Pipe L | m | 15 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.023 |
| | | Coeff.min. | - | 1.07 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-106 | Pipe L | m | 15 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.03 |
| | | Coeff.min. | - | 1.07 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Storage tank | TK-101 | Diameter | m | 1 |
| | | Length | m | 2.2 |
| | | Volume | $m^3$ | 1.73 |

| Equipment | Number | Parameter | Unit | Amount |
|---|---|---|---|---|
| Screw conveyor | S-101 | Diameter | m | 0.23 |
| | | Length | m | 15 |
| | | Height | m | 1.7 |
| | | α | - | 4 |
| Heat exchanger | E-101 | Heat coeff. | $\frac{W}{m^2°C}$ | 800 |
| | | Area | $m^2$ | 4.615 |
| Heat exchanger | E-102 | Heat coeff. | $\frac{W}{m^2°C}$ | 50 |
| | | Area | $m^2$ | 1.416 |
| Heat exchanger | E-103 | Heat coeff. | $\frac{W}{m^2°C}$ | 50 |
| | | Area | $m^2$ | 1.278 |
| Pump | P-107 | Pipe L | m | 820 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.02 |
| | | Coeff.min. | - | 1.07 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-108 | Pipe L | m | 15 |
| | | Height | m | 3.8 |
| | | Pipe D | m | 0.01 |
| | | Coeff.min. | - | 0.6 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-109 | Pipe L | m | 15 |
| | | Height | m | 12.4 |
| | | Pipe D | m | 0.003 |
| | | Coeff.min. | - | 0.77 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Pump | P-113 | Pipe L | m | 15 |
| | | Height | m | 0 |
| | | Pipe D | m | 0.02 |
| | | Coeff.min. | - | 0.9 |
| | | Velocity | m/s | 1.5 |
| | | Efficiency | % | 75 |
| Compressor | C-101 | Efficiency | % | 75 |
| Storage tank | TK-102 | Diameter | m | 3 |
| | | Length | m | 5.9 |
| | | Volume | $m^3$ | 41.7 |
| Storage tank | TK-103 | Diameter | m | 2 |
| | | Length | m | 1.6 |
| | | Volume | $m^3$ | 5.03 |
| Storage tank | TK-104 | Diameter | m | 3 |
| | | Length | m | 8.4 |
| | | Volume | $m^3$ | 59.38 |
| Storage vessel | V-101 | Diameter | m | 2 |
| | | Length | m | 2.8 |
| | | Volume | $m^3$ | 8.8 |

# Appendix 5. Contacts

| **Name** | **Status** | **Contact data** |
|---|---|---|
| Anna van den Bor-Vidolova | Process Technologist at Water Board of Delfland | avandenbor@hhdelfland.nl<br>06 158 259 41 |
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| Peter Baselier | Site Manager at Renewi Hoek van Holland | Peter.Baselier@renewi.com |

**Table 24.** Contact list of people who contributed with information for this report.