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ANAEROBIC DIGESTION OF MUNICIPAL ORGANIC WASTE IN AMSTERDAM

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Title page

Anaerobic digestion of municipal organic waste in Amsterdam
An explorative technical feasibility study and scale comparison.

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Preface

This thesis has been written with the help of many people. I want to use this preface to express my gratitude to some of them.

In the first place, I want to thank my supervisors Ilse Voskamp and Jan Vreeburg. Thank you for your effort and advices. Throughout the process of writing you motivated me to get the best out of myself.

Secondly, I want to thank Houssain Bouhbouh for his help during the data collection process. Thank you for your enthusiasm while conducting the interviews and thank you for translating all the questions and answers.

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Abstract

The urban metabolism of many cities is considered linear. Cities depend on their hinterland for production of resources and disposal of waste. This increases the pressure on availability and affordability of energy and resources. By transforming source-separated organic waste into energy via anaerobic digestion, a community can lower its greenhouse gas emissions and it can become less dependent on external energy suppliers.

This research investigates to what extent anaerobic digestion can contribute to a more sustainable Amsterdam. This research focusses on Amsterdam on city scale and on a neighbourhood in Amsterdam Nieuw West, the Wildemanbuurt. A literature study identifies best practices of anaerobic digestion of municipal organic waste. Companies in the Wildemanbuurt are interviewed to gather data about the local organic waste flows. The Wildemanbuurt can produce 28 ton of biogas out of the 399.8 ton organic waste that is produced per year. When half of the produced energy is required for system operation, anaerobic digestion can provide electricity for 0,4% and heat for 0,2% of the households or natural gas equivalent for 0,4% of the households in the Wildemanbuurt, per year.

In order to do a scale comparison, a multi-criteria analysis with three criteria (environmental, economic and operational aspects) and eight indicators to assess the sustainability of an anaerobic digester on different scales is used. These criteria are used to assess and compare the contribution to sustainability of anaerobic digestion on different scales. Five sets of weights are used; normalised weights (criteria are equally important), weights with an emphasis on environmental aspects, economic aspects or operational aspects and weights assigned by the author. Anaerobic digestion on city scale scores higher on the assessment for every set of weights. Especially on operational aspects the city scale scores high compared to the Wildemanbuurt.

This research shows that anaerobic digestion on neighbourhood scale and on city scale can both contribute to a more sustainable Amsterdam. To what extent anaerobic digestion can contribute depends on scale specific possibility and willingness to invest in technology and the availability of skills and knowledge. Further research is recommended into the Wildemanbuurt, anaerobic digestion technology and waste collection infrastructure.

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1. INTRODUCTION

This first chapter will introduce the topic of this study. The introduction starts with a problem statement to emphasise the urgency and relevance of this research. Urban metabolism is introduced as a tool to evaluate a city's inputs and outputs. Thereafter anaerobic digestion of municipal organic waste is proposed as an opportunity to make Amsterdam more sustainable. This chapter ends with an overview of the structure of this report.

Context

The global population living in urban areas has increased from 33.6% in 1960 to 53.9% in 2015 (Worldbank, 2016). Urban areas are dependent on their hinterland for production of resources and disposal of waste (Bai, 2007). The way today's cities handle their resources is considered linear and therefore leads to environmental pressure on the city itself as well as on a city's hinterlands (Agudelo-Vera, Leduc, Mels, & Rijnaarts, 2012; Leduc, Vera, Rovers, & Mels, 2009). This linearity, where resource inputs are processed into products and waste, is characteristic for most existing cities. The city addressed in this research, Amsterdam, has experienced an average annual increase of inhabitants of 11,000 since 2009 (Gemeente Amsterdam, 2016). The pressure on availability and affordability of energy and resources is encountered throughout different spatial and governmental scales (Gemeente Amsterdam, 2014a).

Urban metabolism

Urban systems differ from natural systems. Although they are similar in the sense that both have inputs which are processed into products and waste, natural systems have a higher resource efficiency and rely on sustainable inputs whereas most existing urban systems have a less sustainable, linear metabolism (C. Kennedy, Pincetl, & Bunje, 2011). From this observation, the question follows whether urban systems can become more sustainable by mimicking natural systems (Y. Zhang, 2013). Zhang, Yang, & Yu (2015) state it is believed it can become possible to reach the efficiency and stability of natural systems in cities by analysing the ecological principles behind an urban system and using the knowledge of ecological systems to design urban systems. This calls for the concept of urban metabolism. Urban metabolism is considered an effective concept to get insight in a city's resource and energy efficiency, quantities of the different flows and potential for recycling (Christopher Kennedy, Cuddihy, & Engel-Yan, 2007; Sahely, Dudding, & Kennedy, 2003; Weisz & Steinberger, 2010). Some urban metabolism studies assess a city as a single organism whereas others see it as an ecosystem in which multiple metabolisms interact (C. Kennedy et al., 2011; Pincetl et al., 2014; Pincetl, Bunje, & Holmes, 2012). To be able to understand the a city as a complex system with multiple processes interacting (Golubiewski, 2012), in this research the concept of urban metabolism examines Amsterdam as if it is an ecosystem with inputs, outputs and storage (C. Kennedy et al., 2011).

Within urban metabolism studies, material flow analysis (MFA) is used as a method to examine flows. More specifically, a MFA examines the flows and stocks of materials in a system within clear spatial and temporal boundaries. The inputs, outputs and flows and stocks within a system are identified. In short this results in the equation: sum of system inputs equals the sum of outputs plus the sum of mass stored. This gives an overview of materials wasted and materials stored in the environment (Brunner & Rechberger, 2003). Recognition of locally sourced and secondary resources is meaningful for the development towards a circular metabolism with sustainable resource management (Agudelo-Vera et al., 2012; Voskamp et al., 2016).

Studying the different processes and interactions that define a system's structure and functioning are essential for improving a city's metabolism (Y. Zhang, 2013). Current urban metabolism studies generally examine flows in a city or a metropolitan area (C. Kennedy et al., 2011). This causes shortcomings for identifying opportunities for improvement on smaller scales. To identify opportunities to improve the urban metabolism on neighbourhood scale, neighbourhood scale analysis is required.

Amsterdam as case study area

The case study area of this research is the municipality of Amsterdam. Within the case study area, city scale and neighbourhood scale are examined. Voskamp et al. (2016) conducted a MFA of Amsterdam on city scale for the year 2012 using a modified urban Eurostat method. The MFA by Voskamp et al. (2016) mapped the different flows in Amsterdam considering local resource inputs, internal flows of secondary resources, throughputs, imports, exports and outputs. To identify options for improvement of the urban metabolism on neighbourhood scale, the organic waste flows in the Wildemanbuurt in Amsterdam are examined in this research.

Anaerobic digestion

Locally sourced renewable energy in Amsterdam currently accounts for 7% of the city's energy consumption. The municipality of Amsterdam set as target that the renewable energy production should increase with 20% in 2020 compared to 2013 (Municipality of Amsterdam, 2015). Currently 2408 TJ is generated from the biomass share in municipal solid waste and from sludge digestion, mainly by a waste fired power plant (de Waart, 2009; Simoës, 2013; Voskamp et al., 2016). When considering Amsterdam and only consider municipal organic waste as an input, the potential is 0.04 PJ per year (Gemeente Amsterdam, 2014b).

There are several options for producing energy from biomass. Main options for treating municipal organic waste while producing energy are incineration, landfilling, composting and anaerobic digestion. Incineration of waste is considered not sustainable due to emissions, relative low energy yield and loss of nutrients (Milutinović, Stefanović, Dassisti, Marković, & Vučković, 2014). Sites for landfilling are limited and composting is a net energy consumer (Li, 2015). Anaerobic digestion appears to be a promising way for treating municipal organic waste while producing energy (Lee, Hidaka, Hagiwara, & Tsuno, 2009; Thenabadu, 2014). Utilising source-separated municipal organic waste in anaerobic digesters can lower the greenhouse gas emissions and will make a community less dependent on external energy suppliers (Curry & Pillay, 2012; Wetenschapswinkel Wageningen UR, 2016). Currently, anaerobic digestion happens at different scales using different types of waste as inputs. Overview of what determines the optimal scale is not available.

Research aims

Since a city scale MFA is unable to describe neighbourhood scale flows and Amsterdam is not using its full biomass to energy potential, the first aim of this research is to map organic waste flows on neighbourhood scale to identify opportunities for anaerobic digestion. And since the optimal scale for anaerobic digestion is unknown, the second aim of this research is to investigate what determines the optimal scale for anaerobic digestion in the case study area.

Both research aims contribute to answering the following main research question:

- To what extent can anaerobic digestion of municipal organic waste contribute to the sustainability of Amsterdam?

Overview

The next chapter describes the case study area and the methods used in this study. The third chapter gives an overview of current anaerobic digestion technologies and concludes with describing an optimal neighbourhood scale anaerobic digester for the case study area. The fourth chapter gives a qualitative and quantitative overview of the organic waste flows in Amsterdam on city scale and neighbourhood scale. In the fifth chapter the two preceding chapters are brought together and the potential for anaerobic digestion of organic waste on neighbourhood scale in the case study area is calculated. The sixth chapter tries to define sustainability in the context of this research. Based on this definition, criteria are formulated for scale comparison. In the seventh chapter anaerobic digestion on neighbourhood scale and city scale are compared and discussed. The discussion continues in chapter eight. The final chapter presents the main conclusions.

2. METHODOLOGY

This chapter starts with an explanation of the research design that is used. Thereafter the case study area and the two scales that are analysed are described. The last part of this chapter explains the research questions and the methods used to answer these. As briefly mentioned in the introduction, this research is divided into two research aims. These two aims result in two sub-questions that both contribute to answering the main question.

Research design

The research method of this study is a case study design. The case study area covers the city of Amsterdam. Within the case study a distinction is made between city scale and neighbourhood scale. By examining Amsterdam on two scales it is possible to collect and compare data of the two scales. Collection and analysis of organic waste data on two scales is required to fulfil the research aims as described in the introduction:

- To map organic waste flows on neighbourhood scale to identify opportunities for anaerobic digestion.
- To investigate what determines the optimal scale for anaerobic digestion in the case study area.

The case study design, in combination with the two research aims, helps to answer the main question. The main research question of this research is:

- To what extent can anaerobic digestion of municipal organic waste contribute to the sustainability of Amsterdam?

The research will be conducted in the case study as described in the next paragraph.

Case study area

This study focusses on anaerobic digestion of organic waste in Amsterdam on neighbourhood and city scale. The Wageningen University Wetenschapswinkel, the Amsterdam institute for Metropolitan Solutions (AMS) and local social entrepreneurs run an anaerobic digestion project in the Wildemanbuurt neighbourhood in Amsterdam (Wetenschapswinkel Wageningen UR, 2016). That project focusses on anaerobic digestion at neighbourhood scale. To perform a scale comparison also the city-wide scale is examined in this research. The spatial boundaries of the case study area are set by the municipal boundaries as described by the municipality, Kadaster and CBS (Gemeente Amsterdam, CBS, & Kadaster, 2016). Within the case study area this research addresses two scales; city scale and neighbourhood scale, the Wildemanbuurt.

City scale

On January 1st 2016 the municipality of Amsterdam counted 834.713 inhabitants (OIS, 2016c), divided over seven city districts. A study done by the municipality shows that currently 27% of the waste in Amsterdam is collected separately with the goal of reuse or recycling (Gemeente Amsterdam, 2015a). Same study shows that 0% of the vegetable, fruit and garden waste is collected separately. Separate collection of vegetable and fruit waste was put to an end to in 2006 because of the low quality of the waste, low participation rate and the focus on energy recovery (Thoden Van Velzen et al., 2013). Recent developments on city scale show a trend towards waste separation at the waste treatment plant. The main waste treatment company in Amsterdam, 'Afval Energie Bedrijf (AEB)', has invested in a sorting installation that should be able to mechanically sort out organic waste, plastics, metals and other recyclables from household waste. The sorting installation is planned to be in function by the end of 2017 (AEB, 2016). To reach the goal of 65% waste separation (Gemeente Amsterdam, 2015b), the municipality of Amsterdam invested in this installation. The efficiency or to what extent this installation contributes to the goal is unclear.

Since this research focusses on the sustainability of the city of Amsterdam, it is interesting to see how sustainability is defined in municipal policy documents.

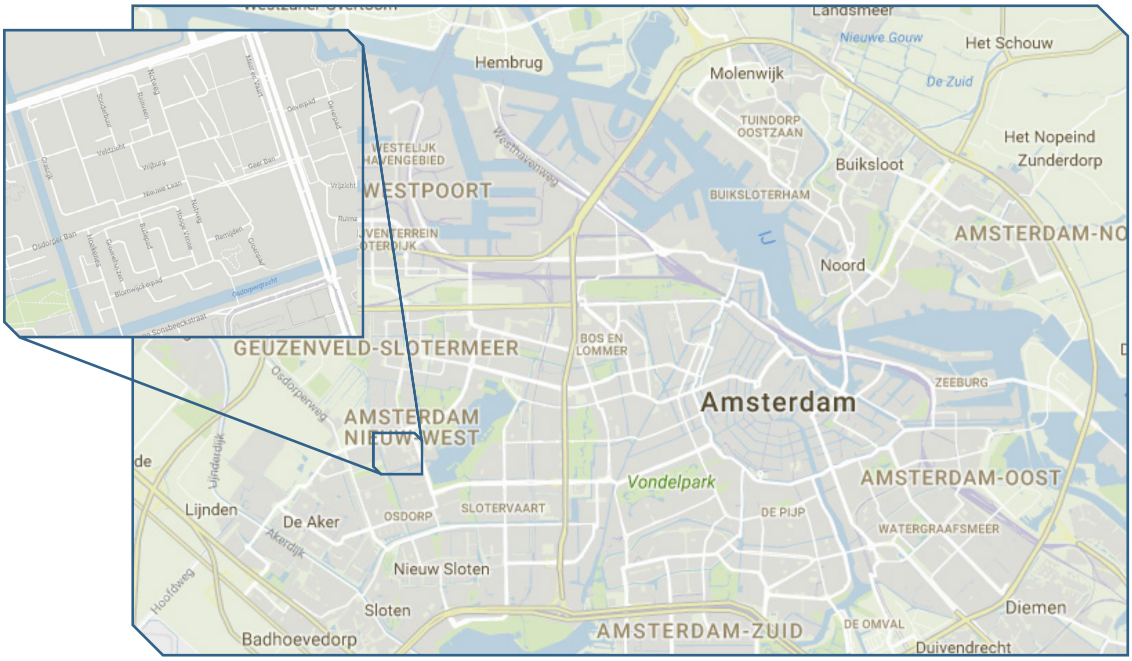


Figure 1. Location of the Wildemanbuurt on the map of Amsterdam (Gemeente Amsterdam, 2017)

The municipality refers in its sustainability agenda to sustainability as a "motor for society and as a driver of the economy" (Municipality of Amsterdam, 2015, p. 7). Even though this is not a definition, it could show the intentions of the municipality. The municipality claims a more sustainable Amsterdam is beneficial for society as well as for the economy of the city.

In the same document five pathways towards a more sustainable Amsterdam are pointed out. These five pathways are;

1. Renewable energy;
2. Clean air;
3. Circular economy;
4. Climate resiliency and
5. Sustainable own operational management.

The first pathway pronounces that more energy should be produced from renewable sources and less energy should be consumed. The second pathway aims at cleaner air solely through cleaner mobility. The third pathway calls for more separation of waste flows. In a broader sense it aims at realising a circular economy with new ways of production, distribution and consumption. The fourth pathway focusses on making the city resilient to effects of climate change. Lastly the municipality wants to make its own operational activities more sustainable through sustainable procurement (Gemeente Amsterdam, 2015b).

Neighbourhood scale - The Wildemanbuurt

The Wildemanbuurt is a residential area in the west of Amsterdam, located in the city district of Amsterdam Nieuw West (figure 1). The area exists of approximately 2400 houses of which 98% are multi-storey apartment buildings (Wetenschapswinkel Wageningen UR, 2016). The Wildemanbuurt has approximately 4800 inhabitants. 27% of the inhabitants is 65 years or older, in Amsterdam in total this is 12% (OIS, 2016b; Wetenschapswinkel Wageningen UR, 2016). 58% of the inhabitants is immigrant, in Amsterdam in total this is 52% (OIS, 2016a; Wetenschapswinkel Wageningen UR, 2016).

The boundaries of the Wildemanbuurt are the 'Ookmeerweg' on the north, the 'Meer en Vaart' on the east, the 'Osdorpergracht' on the south and the canal on the east.

Currently there is no infrastructure for separate collection of vegetable and fruit or garden waste. Organic waste is collected together with the other waste and is incinerated (Wetenschapswinkel Wageningen UR, 2016). Since summer 2016 there is a bread digester active that originates from a previous project that had to tackle a hygiene problem. Moreover, in some religions it is not allowed to throw away leftover bread. Therefore the leftover bread is fed to ducks and birds in the park. However, sometimes there was more bread in the parks then the ducks and birds could eat which attracted rats. This set in motion a project that designed the anaerobic bread digester. Due to its low efficiency and capacity, it serves currently a communicational purpose. It informs the people that it is possible to transform waste into energy. Local social entrepreneurs from the 'Lucas Community' and 'The Beach' combined forces with the

Wageningen University Wetenschapswinkel and the AMS to investigate the possibilities for designing a new digester for the Wildemanbuurt. This new anaerobic digester had to be able to digest more types of organic waste and the produced energy should be beneficial to the neighbourhood.

Research questions

Two sub-questions are used to answer the main question. First the main question is explained, afterwards the two sub-questions including methods used to answer these are presented.

Main question:

- To what extent can anaerobic digestion contribute to the sustainability of Amsterdam?

The main question can be divided in three parts. First part is the anaerobic digestion technology and the technology's potential to increase the sustainability of an urban area. This first part is covered in the first sub-question. The second part considers the definition of sustainability. The third part continues on this by describing how scale can influence the ability of anaerobic digestion to contribute to a city's sustainability. The second sub-question covers the second and third part of the main question. The second sub-question will describe criteria to define the sustainability of an anaerobic digestion technology. Next to that, the second sub-question will analyse what determines the optimal scale for anaerobic digestion.

Sub-question 1

- What is the optimal anaerobic digestion installation on neighbourhood scale and what is the potential of anaerobic digestion on neighbourhood scale?

Anaerobic digestion

First a literature study was done to identify best practices of anaerobic digestion of municipal organic waste flows. Scientific literature was used for this literature study. The literature study resulted in an overview of current anaerobic digestion technologies. Next to that, characteristics that categorise different types of digesters are defined. Based on these characteristics and on characteristics of the Wildemanbuurt, an ideal neighbourhood scale anaerobic digestion installation is described.

Overview of the organic waste on city and neighbourhood scale

Secondly, this research question resulted in overview of the characteristics of organic waste on both scales of the case study area. This overview provided insight in the types of organic waste as well as the size of the flows at both scales. To answer the second part of this research question data was gathered from literature and by conducting interviews in the case-study area.

City scale

To describe the waste characteristics on the city, two main literature sources were used;

- A study on the waste chain done by the municipality (Gemeente Amsterdam, 2015a).
- A material flow analyses of Amsterdam done by Voskamp et al. (2016).

The second study is a modified Eurostat MFA of Amsterdam. The modified Eurostat method for MFA used in this study is different compared to a conventional MFA since it takes into account some of the processes that happen within the system under research. Whereas a conventional MFA takes the system as a 'black box', the modified method includes the locally sourced renewable and secondary resources.

Neighbourhood scale

To describe the waste characteristics of the inhabitants of the Wildemanbuurt and create a neighbourhood scale MFA, literature and interviews were used. Data about the household organic waste was gathered from research done by a consultancy firm commissioned by the municipality. In that study waste characteristics of the city district Nieuw West are described (CREM, 2013). This data is not specific for the neighbourhood scale of the case study area. Due to lack of more detailed data it was assumed to be applicable to the Wildemanbuurt since the Wildemanbuurt is located in the city district Nieuw West. Additionally, neighbourhood specific data was gathered through interviews in the area. The answers to the questions provided an overview of the type and amount of organic waste that is generated by the companies in the Wildemanbuurt. In total 16 companies were interviewed:

- 5 restaurants,
- 3 snackbars and fish shops,
- 5 bakeries,
- 4 other shops.

This adds to a total of 17 interviews since one company served as a restaurant as well as a bakery. Only companies that produced organic waste were interviewed. Also, two bigger supermarkets were left out of this research since these were to follow corporate waste treatment strategies and therefore unable to join an anaerobic digestion program. All the selected companies were willing to participate in the interviews. A total list of interviewed companies is presented in annex 1.

The interviews were structured and had open-format questions (Walliman, 2006). Moreover, every interviewee got the same questions in the same order. Because of the open-format questions every respondent could express answers in its own way. The interviews were done face-to-face. A translator was used to translate questions and answers, since many of the respondents preferably answered in Arabic. The following questions were asked:

- What kind of organic waste do you have?
- How much organic waste (in weight) do you produce per unit of time?
- What are the characteristics of this flow (dry, wet, polluted, etc.)?
- What is currently done with this waste within your company?

The interview format that is used is presented in annex 2. The results of the literature study combined with the neighbourhood analysis made it possible to describe an anaerobic digestion system that suits the conditions in the Wildemanbuurt. This made it possible to calculate the energy potential and answer sub-question 1.

Sub-question 2

- What determines the optimal scale for anaerobic digestion of organic waste in Amsterdam?

The second sub-question focussed on comparing anaerobic digestion on neighbourhood scale and anaerobic digestion on city scale. This comparison was done with a multi-criteria analysis (MCA). In order to assess the sustainability of a project, product or policy including its activities and consequences, an assessment tool is needed. This assessment tool is based on a measurable definition of sustainability. Sustainability can be measured when all aspects of the definition are split into assessable criteria. Criteria can be conflicting, both quantitative and qualitative and expressed in different units. Since a MCA is capable of working with these different approaches in one assessment tool, it is in this case the most suitable method for assessing sustainability (Milutinović et al., 2014).

A MCA combines qualitative and quantitative data in criteria that can be rated or ranked (Mendoza et al., 1999). How the different criteria are weighted depends on the preferences of the stakeholders (Lahdelma & Hokkanen, 2000). To do this MCA, first a literature review was done to identify the sustainability criteria suitable for assessing the sustainability of anaerobic digestion on city and neighbourhood scale. Secondly, both scales were scored along the criteria. Third, the scores of both scales were compared. This research did not decide whether city or neighbourhood scale is more sustainable. It investigated how relative preference of criteria decides what kind of anaerobic digester on a certain scale is best.

As mentioned in the case area description, the city of Amsterdam has clear ambitions considering sustainability. The municipality's policy on sustainability is used as guideline to discuss Amsterdam's view on sustainability. The following policy documents are used:

- De Circulaire Metropool: Amsterdam 2014-2018 (Gemeente Amsterdam, 2014a)
- Duurzaam Amsterdam (Gemeente Amsterdam, 2015b)
- Structuurvisie Amsterdam 2040: Economisch sterk en duurzaam (Gemeente Amsterdam, Zanen, Ponteyn, & Keijzer, 2011)

By making sustainability measurable, it is possible to answer the main question. Also, scoring the sustainability of operations on both scales is required to be able to answer the second part of this sub-question. The method used for doing the MCA is based on Seghezzo (2004). Scores are assigned based on literature, assumptions and experienced gained during this research. Three criteria are used for assessment; environmental aspects, economic aspects and operational aspects. Five sets of weights are used, normalised weights (criteria are equally important), weights with an emphasis on environmental aspects, weights with an emphasis on economic aspects, weights with an emphasis on operational aspects and weights assigned by the author. Further explanation of this sustainability assessment method is presented in chapter six.

The structure of this research and how the different research questions relate to each other is visualised in figure 2 on the next page.

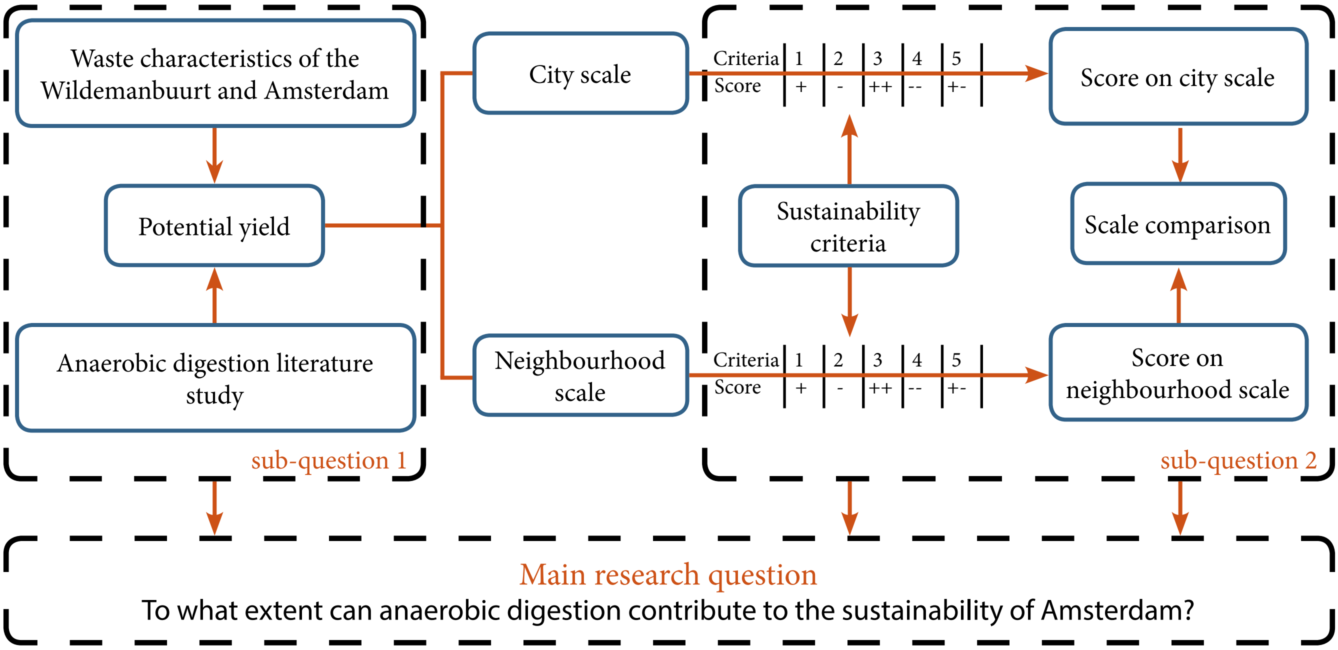


Figure 2. Structure of this research

3. ANAEROBIC DIGESTION OF MUNICIAPL ORGANIC WASTE

This chapter gives an overview of the technology of anaerobic digestion of the organic fraction of municipal solid waste. Anaerobic digestion is one of the options to improve the urban metabolism of Amsterdam. To work towards a circular metabolism, outputs need to be transformed into inputs (Girardet, 2017). In short, anaerobic digestion helps closing the cycle by transforming the output of the conventional system (waste) into potential new inputs of energy and fertiliser.

First the biological process is described. Then the different types of digesters and characteristics that distinguish them are discussed. In the end of this chapter the possible biogas yield of a neighbourhood scale anaerobic digester is presented.

The biological process

Anaerobic digestion is a biological process in which organic matter is broken down into smaller particles by reactions absent of oxygen (Adekunle & Okolie, 2015). The process and how the steps relate to each other is presented in figure 3. Anaerobic digestion is used to treat and break down waste while at the same time produce biogas and digestate that can be used as fertiliser. An anaerobic digester can be designed to treat different waste flows, for example municipal solid waste, municipal organic waste, industrial waste or sludge from a wastewater treatment plant. Next to different input flows, an anaerobic digester is designed with a certain capacity to treat for example one building, a street, a neighbourhood or an industrial site.

Pre-treatment

As can be seen in figure 3, before the anaerobic digestion takes place, the waste has to go through pre-treatment. For organic waste this treatment step prior to the actual anaerobic digestion usually happens to take out non-digestible particles such as stones, plastics and metals. Pre-treatment also mixes the waste flow to get a homogenous substance. Mixing increases the distribution of waste particles and anaerobic digestion microorganisms throughout the reactor (Li, 2015). Pre-treatment also decreases the particle size, all in order to increase the biodegradability (Zupan, D & Grilc, 2007). By decreasing the particle size the effective surface of the waste particles increases which improves the anaerobic digestion process because it increases the contact area between waste particles and bacteria (Ariunbaatar, Panico, Esposito, Pirozzi, & Lens, 2014).

The biological process consists of four stages; hydrolysis, acidogenesis, acetogenesis and methanogenesis (figure 3).

1. Hydrolysis

In the first stage, the hydrolysis, the organic matter turns into liquefied monomers, polymers and acids. Basically the complex organic molecules are broken down into smaller sugars which can be taken up by bacteria in the other stages (Ostrem & Themelis, 2004). Hydrolysis is considered the speed limiting step for the anaerobic digestion process because hydrolysis happens very slow (Li, 2015). It is difficult to increase the speed of hydrolysis or to upscale hydrolysis due to the formation of toxic and other unwanted by-products and because of the high energy demand of hydrolysis (Adekunle & Okolie, 2015; Li, 2015; Mata-Alvarez, Macé, & Llabrés, 2000; Salihu & Alam, 2016).

2. Acidogenesis

In the second stage, the acidogenesis, bacteria transform products from the hydrolysis into short chain volatile acids, alcohols, hydrogen and carbon dioxide. The hydrogen, carbon dioxide and acetic acids will skip the third step, the acetogenesis, because these are ready to be used in the fourth step (Ali Shah, Mahmood, Maroof Shah, Pervez, & Ahmad Asad, 2014).

3. Acetogenesis

In the acetogenesis stage the volatile acids and alcohols

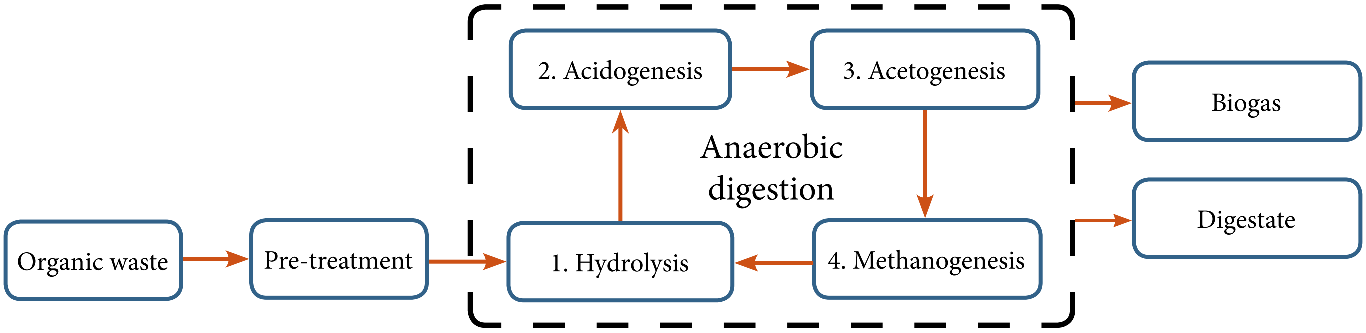


Figure 3. Schematic oveview of the anaerobic digestion processes

are transformed into hydrogen, carbon dioxide and acetic acids, which can be utilised in the methanogenesis stage (Adekunle & Okolie, 2015).

4. Methanogenesis

During this fourth stage the hydrogen and acetic acids are converted into biogas, consisting of methane gas and carbon dioxide. This reaction is performed by methanogens and happens under anaerobic conditions (Curry & Pillay, 2012).

Output of biogas and digestate

These four stages together form the process of anaerobic digestion. The process has two outputs; biogas and digestate. The type of organic waste and the way the process is managed determines the composition of the biogas (Ali Shah et al., 2014). The three main components of biogas typically are methane (CH4) 50-75%, carbon dioxide (CO2) 20-45% and water 2-7% (de Graaf & Fendler, 2010). Biogas can be used to produce thermal and electrical energy (Ali Shah et al., 2014). After post-treatment, the digestate can be used as a soil conditioner because of its high nutrient content (Ostrem & Themelis, 2004). By using the digestate as fertiliser, nutrients like nitrogen (N), phosphorus (P) and potassium (K) are recovered and reused (de Mes, Stams, Reith, & Zeeman, 2003). The quality and possibilities for further use of the digestate depend on the type of anaerobic digestion process, the pre-treatment steps taken and the type of feedstock that was used (Balat & Balat, 2009; De Wilde, Van Eekert, Van der Zee, & Peuckert, 2014). Therefore, the type of post-treatment steps required also differ. All particles that are not taken out during pre-treatment or degraded during the anaerobic digestion process end up in the digestate. Depending on the previous treatment steps, the digestate is usually dewatered, unwanted particles are removed and then it is composted for stabilisation of the organic matter (De Wilde et al., 2014).

Types and characteristics

The basic biological principles of the anaerobic digestion process, as discussed in the previous paragraph, are almost the same in any anaerobic digester. However, there are some physical and operational characteristics that divide anaerobic digesters in several types. These characteristics are discussed in this paragraph.

Dry or wet influent

A distinction in anaerobic digestion technologies can be made between dry and wet influent. Wet processes use more fresh water than the dry processes. Wet influent has a dry solids content of around 10 – 15%. Dry influent has at least 25% dry solids (Li, 2015). The amount of water required for the desired process is added to the waste substance before it is fed to the reactor. Commercial technologies such as Dranco, Valorga, Linde and Kompogas use influents with 30 to 40% total solids. (Bolzonella, Pavan, Mace, & Cecchi, 2006). More wastewater is produced in a wet process than in a dry process. Dry anaerobic digestion requires less energy for operating (Li, 2015). In wet processes, the rate at which organics can be added is higher (Luning, Van Zundert, & Brinkmann, 2003). Dry processes are most used in Europe with 65% of the total anaerobic digestion capacity compared to 35% wet processes (De Wilde et al., 2014).

Yield in biogas per kilogram of waste input is almost the same for both dry and wet influents (De Wilde et al., 2014; Luning et al., 2003). There are studies claiming that dry process require a smaller reactor volume because there is less water added to the flow (Cecchi, Bolzonella, Pavan, Macé, & Mata-Alvarez, 2011). But there are also studies claiming the opposite, that wet influent processes require smaller reactor volumes because of the higher loading rate of organic matter (Luning et al., 2003).

Continuous or batch processes

Another distinction can be made based on the feeding method. A batch process works with cycles in which the anaerobic digestion process is fed with new feedstock on a regular basis, for example every day or once a week. On the other hand, continuous processes have constant input of waste and a continues output of biogas (Rapport, Zhang, Jenkins, & Williams, 2008; Thenabadu, 2014).

Whether the reactor is fed in a batch or continuous way, the rate at which organic matter is loaded into the reactor is an important parameter for successful anaerobic digestion. Too high loading rates lead to an increase in acidogenic bacteria (step 2, figure 3). High concentrations of acidogenic bacteria make the pH value drop (Ostrem & Themelis, 2004). Methanogenic bacteria die at low pH values and without methanogenic bacteria there is no biogas production. So the loading rate has to be calculated and maintained carefully in order to prevent a system crash.

A batch process with dry influent requires less pre-treatment and less mixing equipment and is therefore considered cost-effective (Li, 2015; Muzenda, 2014). On the contrary, a dry batch process produces 20% less methane than continuous processes and a batch reactor requires more volume than a continuous reactor (Arsova, Themelis, & Chandran, 2010; De Wilde et al., 2014).

One or two-phase digesters

Further distinction can be made between one-phase and two-phase digesters. In a one-phase digester all four processes happen in the same reactor. This reactor has conditions suitable for all phases, not specifically for one. In a two-phase system the first reactor has optimal conditions to perform the hydrolysis, acedigenesis and the acetogenesis. After the first reactor the methanogenesis happens in the second reactor. Both reactors are designed with optimal conditions for the reactions that have to happen (Li, 2015; Ostrem & Themelis, 2004).

Two-phase processes are most suitable for flows with highly biodegradable wastes such as separately collected organic waste, since this process can handle higher loads in the digester (Forster-Carneiro, Fernández, Pérez, Romero, & Álvarez, 2004). However, one-phase systems are prevailing on an industrial scale (Mata-Alvarez et al., 2000). One-phase digesters are with 93% of total digesters most commonly used. This is mostly due to higher investment and operational cost for two-phase systems (De Baere & Mattheeuws, 2013). Also, one-phase digesters are easier to operate because they do not require very specific technical operation skills (Li, 2015).

Mesophilic or thermophilic processes

Temperature has a strong influence on the anaerobic digestion process. A change in temperature of only a few degrees already has a strong effect on the activity of the microorganisms (Li, 2015). In general a division can be made between mesophilic and thermophilic processes. Mesophilic processes happen at lower temperature (30-38 °C) than thermophilic processes. Therefore, these systems require less external energy inputs than thermophilic processes. This has as consequence that the gas production and the operation speed are lower than at thermophilic processes. Thermophilic processes on the other hand happen at higher temperature (50-60 °C) and do require more external energy input. This leads to higher gas production at higher speed with thermophilic processes than with mesophilic processes (Environment Canada, 2013). Advantage of a mesophilic process is that the bacteria are more resistant to fluctuation in environmental conditions such as temperature (Li, 2015).

Wildemanbuurt anaerobic digester

Based on the characteristics of the Wildemanbuurt and the waste it produces an optimal anaerobic digestion set-up can be described. Based on the characteristics of this specific set-up a potential yield can be determined.

To be able to make a decision for a certain type of anaerobic digester for the Wildemanbuurt, some assumptions are made about characteristics of the Wildemanbuurt and about anaerobic digestion on neighbourhood-scale in general. These assumptions are based on personal communication with people involved with the Wildemanbuurt and on logical reasoning. The main assumption is that compared to a city or district scale, the organisation responsible for anaerobic digestion has less technical and financial resources at its disposal on a neighbourhood-scale. The decision for a certain technology is therefore mostly based on operational and financial aspects.

The anaerobic digestion installation that seems most appropriate for the Wildemanbuurt is a one-phase mesophilic batch reactor with dry influent. Figure 4 on the next page is a tree-diagram that presents the different options for anaerobic digestion. The chosen setup is marked in orange. The following paragraphs discuss per process characteristic what seems most appropriate for the Wildemanbuurt.

Dry or wet

A dry influent process seems most appropriate for the Wildemanburt. Main reasons for this are that less fresh water is required, less wastewater is produced and less energy input is required (Li, 2015). Also, wet influent systems experience more system failure (De Wilde et al., 2014). To overcome system failures, technical expertise is required which could be lacking in the Wildemanbuurt.

One or two-phase

As mentioned before, running an one-stage digester requires less operational skills than running a two-phase digester (Li, 2015). Next to that , the invest and operational costs are lower for a one-phase digester (De Baere & Mattheeuws, 2013). These two arguments make an one-phase system more suitable for the relative small scale on which a neighbourhood-scale digester operates.

Continuous or batch

A batch process requires less pre-treatment and less mixing equipment than a continuous process. This means the digester requires less investment costs, operational skills and surface area. The gains in surface area could be counterbalanced by the requirement of a bigger reactor at a batch process. Due to the lower costs and less skills required, a batch process is considered the more suitable process for a neighbourhood-scale digester.

Mesophilic or thermophilic

Even though a thermophilic process has the advantage of a higher yield, it cannot offset disadvantages of a higher energy demand and low resistance to temperature fluctuations. In a less professional setting that a neighbourhood-scale digester could experience, it is more difficult to keep the environmental parameters constant due to lack of availability of technical equipment and staff. Therefore a mesophilic process is more suitable for the Wildemanbuurt.

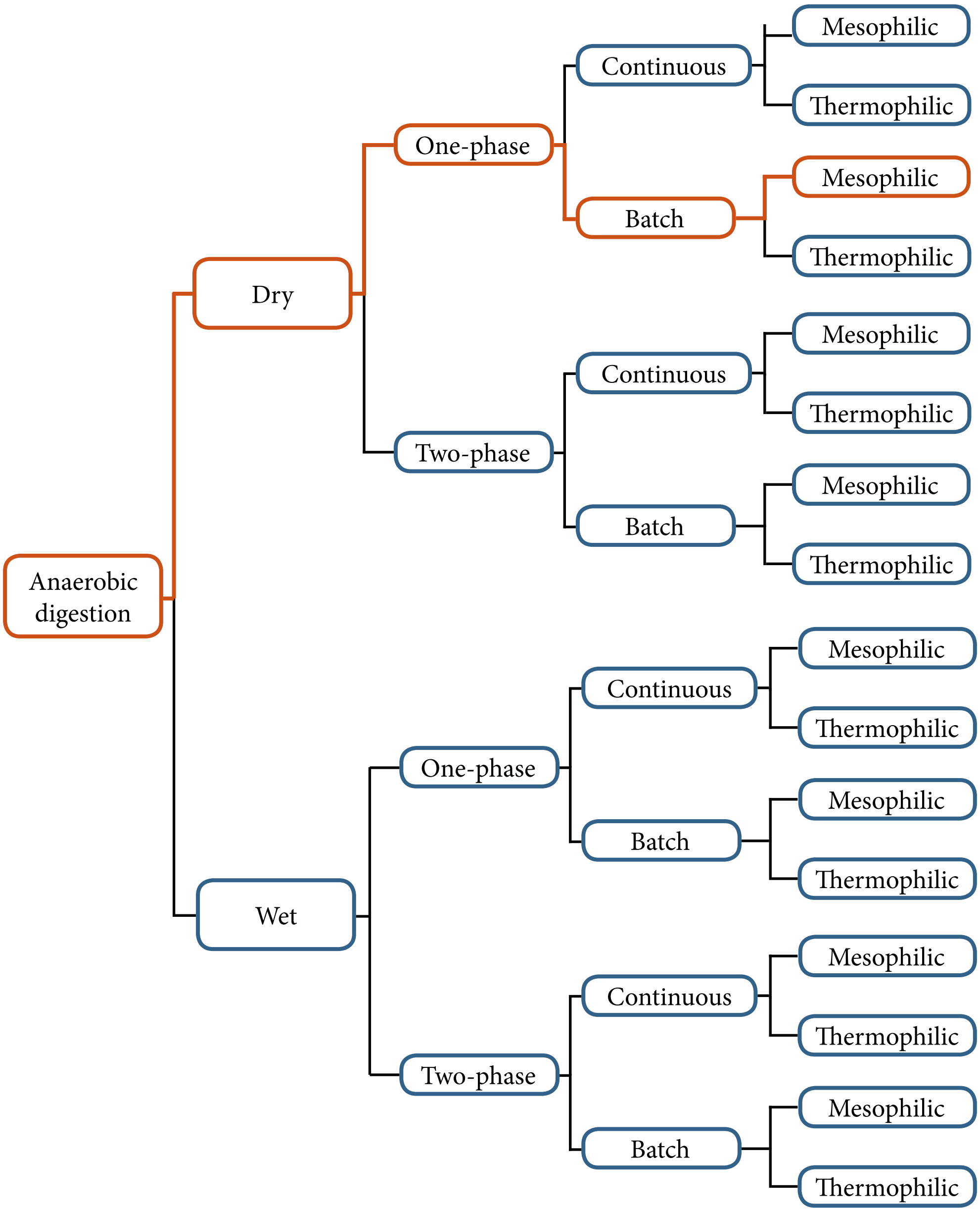


Figure 4. Figure 4 Visual presentation of different anaerobic digestion installations based on the process characteristics. Most appropriate installation for the Wildemanbuurt is presented in orange.


ROXY

4. CHARACTERISTICS OF THE MUNICIPAL ORGANIC WASTE

This chapter presents an overview of the organic waste flows in Amsterdam, on city scale and for the Wildemanbuurt. To be able to explore the potential for anaerobic digestion, this chapter provides an overview of the different types of waste, the amounts and the current infrastructure for dealing with it. First the situation in Amsterdam on city scale will be discussed, thereafter the Wildemanbuurt is addressed.

Amsterdam

As mentioned in the methodology, city scale organic waste data was gathered from two main sources. Firstly, the municipality of Amsterdam did a qualitative and quantitative analysis of the waste in Amsterdam for the year 2014 (Gemeente Amsterdam, 2015a). This study investigated the type of waste streams in Amsterdam and measured their size. This study included household waste

Table 1 Waste collected separately in Amsterdam in the year 2014-2015

Type of waste	**Amount per capita** (kg)	**Total for Amsterdam** (kt)
Bulky household waste	46,1	38,4
Paper	23,4	19,5
Glass	18,4	15,4
Metals	7	5,8
Textile	2,7	2,3
Plastic	1,8	1,5
Small chemical waste	0.3	0,3

Source: Gemeente Amsterdam, 2015a

Table 2 Waste collected not separately in Amsterdam in the year 2014-2015

Type of waste	**Amount** (kg)	**Total for Amsterdam** (kt)
Vegetable and fruit	79,4	66,3
Paper	38,6	32,2
Other	33,7	28,1
Plastic	21,7	18,1
Sanitary[1]	21,6	18,0
Bulky household waste	20,5	17,1
Textile	14,2	11,9
Glass	13,4	11,2
Garden	12,5	10,4
Remainder[2]	16	13,4

[1] diapers etc.
[2] all remaining waste including cat litter, metals, drink cartons and small chemical waste

Source: Gemeente Amsterdam, 2015a

Table 3 Organic household waste produced per year in the Wildemanbuurt

Type of waste	**Amount per capita** (kg)	**Amount in total** (t)
Vegetable and fruit	64,4	309,3
Garden	27,5	131,8
Food	10,0	48,2
Bread	3,2	15,2
Organic residues	0,5	2,5

Source: (CREM, 2013)

and waste from companies comparable to household waste in amount and composition. The results of this study and an overview of the waste streams in Amsterdam are presented in table 1 and table 2. Table 1 shows the amount of waste collected separately. The waste flows that are not collected separately are presented in table 2.

The flows of vegetable and fruit, and garden waste are interesting for anaerobic digestion. In Amsterdam this is 91,9 kg per year, which accounts for 24,8% of the total waste. Currently, none of this is collected separately.
Voskamp et al. (2016) showed that a total of 373 kt of household and commercial waste and sludge is incinerated with energy recovery. Next to that, 3 kt (household) and 100 kt (industrial) waste is anaerobically digested in Amsterdam. 34 kt waste is recycled and no waste is landfilled. Flows to nature are emissions to the air (4,712 kt), emissions to water (83,255 kt) and dissipative flows (4,769 kt).

Wildemanbuurt

Since there are no industries present in the neighbourhood, household waste and waste from small companies makes up the majority of the waste flow in the Wildemanbuurt. As presented in figure 5, the majority of the neighbourhood is covered by residential area. Besides two streets for commercial activities, there is one mosque in the Wildemanbuurt. To be able to compare both scales, the same type of data and units should be used at both scales. On city scale, household waste and waste from companies comparable in amount and composition is taken into account. This chapter includes household waste and waste from small companies.

Household waste

This paragraph will look at the waste produced by the households in the Wildemanbuurt. The most detailed data available was about household waste production in the city district Nieuw West, in which the Wildemanbuurt is located. This data comes from a study that analysed the composition and volume of waste in different city districts in Amsterdam for the year 2012. It showed that 278 kg/cap/year of not separated waste is collected (CREM, 2013). Organic waste makes up for 38% of this flow. The organic waste flow exists of vegetable and fruit waste (61%), garden waste (26%), food waste (9,5%), bread (3%) and organic residues (0,5%) (CREM, 2013).
Approximately 4800 people live in the Wildemanbuurt (Wetenschapswinkel Wageningen UR, 2016). An overview of the organic waste flow per capita and in total produced by residents in the Wildemanbuurt, based on data from CREM (2013), is presented in table 3.

Waste from small businesses

Local small businesses are a source of organic waste as well. The types of companies present in the Wildemanbuurt are bakeries (3), restaurants (4), snackbars and fish shops (2) and other shops (3). The number behind every category represents the number of companies used for this research. Based on the interview results, the waste

Figure 5. Map of the Wildemanbuurt presenting the different functions

produced by these companies can be classified in five types (table 4).

Interviews in the neighbourhood show that the flow from all businesses in the Wildemanbuurt exists for 11% out of bread, for 9% out of swill, for 34% out of other waste, for 19% out of frying oil, for 18% out of offal and for 8% out of fruits and vegetables. Overview of the organic waste produced by companies in the Wildemanbuurt based on the interviews is presented in short in table 5 and in detail in annex 3.

The sources and flows are presented in a sankey diagram (figure 6, next page). In this diagram is visible that the current system has clear inputs, these inputs are transformed to waste and leave the system again as outputs. The bread waste that is produced by bakeries and bread waste from one of the restaurants (Lunchroom Soussi) is picked up by local farmers and is used as animal feed. One bakery (Cesme Bakerij en Lunchroom) participates in the bread digester project and has its bread picked up and used in the digester. The bread waste from other restaurants and from households leaves the system with the other unseparated waste. This waste flow also includes the swill from restaurants and is picked up by the waste treatment company. Representatives of the interviewed companies explained that the frying oil is picked up by a company specialised in treating it. Also, it is obliged by law to collect and treat offal separately (European Parliament and Council, 2009). There is no separate collection of fruits and vegetables or non-professional food waste in the Wildemanbuurt, this all leaves the system with the unseparated waste.

This chapter gave an overview of the amount and types of organic waste on city scale in Amsterdam and on neighbourhood scale in the Wildemanbuurt. In the next chapter the potential for anaerobic digestion of the total organic waste flow in the Wildemanbuurt is estimated.

Table 4 Types of waste produced by companies in the Wildemanbuurt

Type of waste	Characterisation
Bread	As mentioned in the methodology, because of religious motivations bread is usually not thrown away or considered as waste in the Wildemanbuurt. Bakeries currently transport it to local farms where it serves as animal feed.
Swill	Cooked and uncooked food waste and other professional kitchen waste. Can be of use as food for animals.
Frying oil	Originates from kitchens in restaurants, snackbars and fish shops. This flow is interesting for methane production, even if it comes in low volumes, due to the high energy content of lipid-rich oils (Martín-González, Colturato, Font, & Vicent, 2010).
Offal	Waste produced during meat preparation. Exists mostly of animal meat and bones.
Fruits and vegetables	Originates from restaurants and shops and is usually not collected separately. It has seasonal changes due to changing availability of fruits and vegetables throughout the year.
Others	Some companies were not able to specify their organic waste flow. These companies considered all their waste as one flow. Therefore, in this research the 'Others' waste flow is a mix of organic and inorganic waste. This flow originates from the companies that were not able to specify their organic waste.

Table 5 Organic waste produced by companies in the Wildemanbuurt in kg per week.

Source	Bread	Swill	Frying oil	Offal	Fruits and vegetables	Others
Restaurants	6	75	7,2	0	0	120
Snackbars & fish shops	0	15	187,4	130	0	105
Bakeries	102,5	0	0	0	0	90
Shops	0	0	0	55	79,5	30
Total	108,5	90	194,6	185	79,5	345

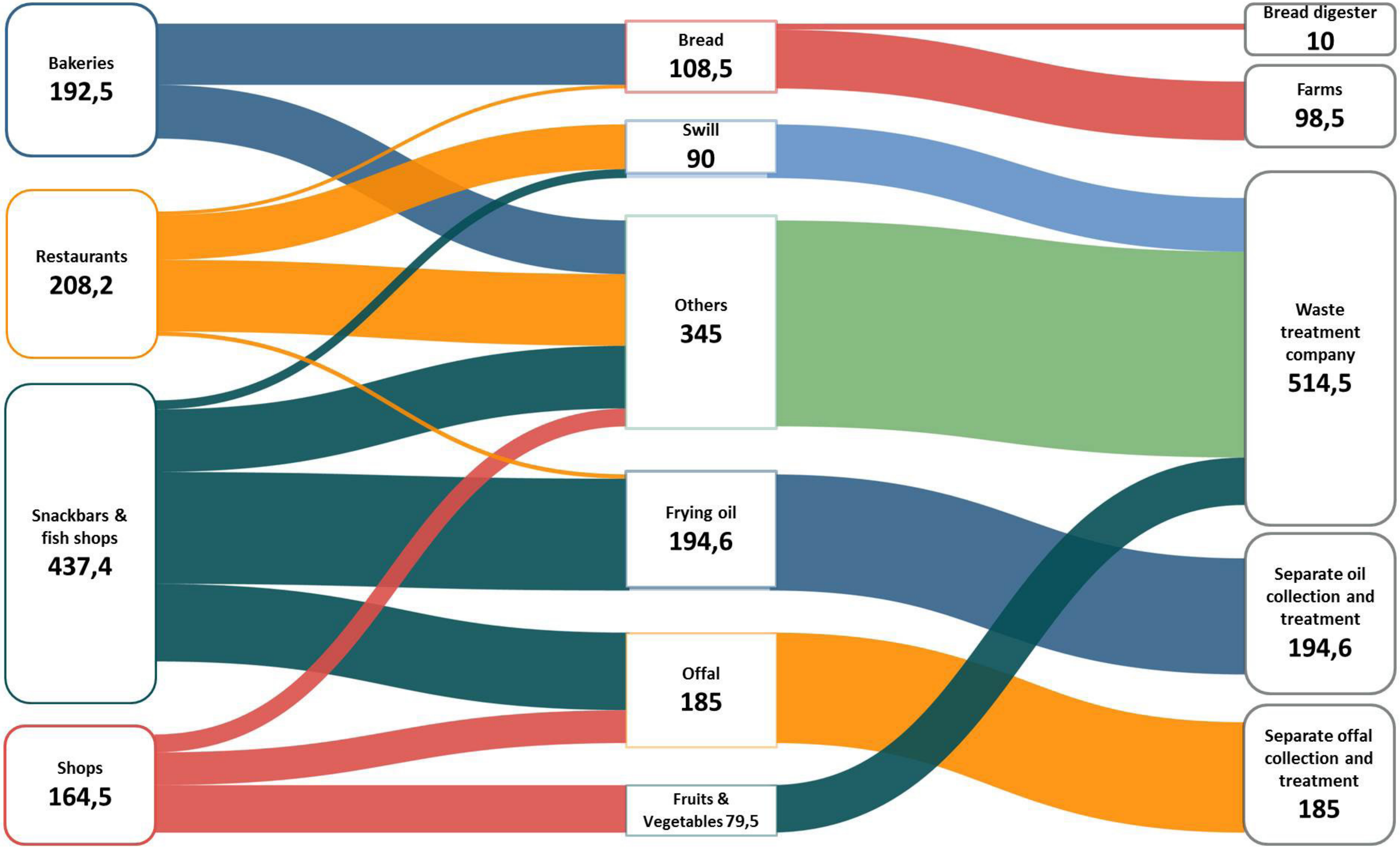


Figure 6. Sankey diagram of the organic waste flows produced by companies in the Wildemanbuurt in kilogram per week

5. POTENTIAL FOR THE WILDEMANBUURT

By bringing together the waste characteristics as presented in chapter 4 and the anaerobic digestion technology as presented in chapter 3, the potential for anaerobic digestion in the Wildemanbuurt is estimated in this chapter. First, the part of the organic waste suitable for anaerobic digestion is identified and quantified. The paragraph thereafter presents the mass and energy balance of the projected anaerobic digester. After that the energetic value of the produced biogas is calculated and compared with the current energy consumption in the Amsterdam.

Waste in the Wildemanbuurt

Interviews were conducted in the Wildemanbuurt to get an overview of the different organic waste flows specific for this case study area. The amount of produced waste per source is presented in table 6.

As mentioned before, the law provides clear guidelines how to deal with offal. It is not allowed to treat it together with other waste flows (European Parliament and Council, 2009). Therefore offal is considered not useful for anaerobic digestion in the Wildemanbuurt and it is left out of further calculations. The interview questions were focused on identifying the organic waste flows. However, some companies also mentioned details about their unseparated other waste flow. This was mostly because these companies did not separate all their waste and therefore some organic waste ended up in the other waste flow. The organic content of this waste flow differs per company and is unknown. Therefore it is not taken into account in further calculations. Lastly, the garden waste is left out of further anaerobic digestion calculations. The amount of garden waste is calculated on data specific for the city district of Amsterdam Nieuw West. As mentioned in the introduction, in the Wildemanbuurt 98% of the people live in multi-storey apartment complexes without gardens. Therefore garden waste is left out of the calculations.

With swill, frying oil, bread, fruits and vegetables, food and organic residues taken into account the total organic waste flow in the Wildemanbuurt is 7688,6 kg per week (table 7).

Table 6 Organic waste produced in the Wildemanbuurt in kg per week

	Type of waste								
Source	Swill	Frying oil	Bread	Fruits and vegetables	Food	Organic residues	Offal	Others	Garden
Restaurants	75	7,2	6	0	-	-	0	120	0
Snackbars & fish shops	15	187,4	0	0	-	-	130	105	0
Bakeries	0	0	102,5	0	-	-	0	90	0
Shops	0	0	0	79,5	-	-	55	30	0
Households	0	0	292,5	5948,3	926,4	48,8	0	-	2535,4
Total	90	194,6	401	6027,8	926,4	48,8	185	345	2535,4

Table 7 Organic waste flows used for calculations

Flows	Total per week in kg	Total per year in kg	Total per year in ton
Swill	90,0	4680	4,68
Frying oil	194,6	10119,1	10,1
Bread	401	20854,2	20,9
Fruits and vegetables	6027,8	313447,9	313,4
Food	926,4	48171,8	48,2
Organic residues	48,8	2535,4	2,5
Total	7688,6	399808,4	399,8

Anaerobic digestion in the Wildemanbuurt

As presented in chapter three, it is advised to use an one-phase mesophilic batch reactor with dry influent in the Wildemanbuurt. This is commercially available as a 'Biocel' reactor (de Mes et al., 2003; De Wilde et al., 2014; Li, 2015; Ten Brummeler, 2000). A full scale Biocel installation is active in Lelystad, The Netherlands. This plant has a capacity of 50,000 tons per year, a lot more than the 399,8 tons that the Wildemanbuurt produces(Li, 2015; Ten Brummeler, 2000). However, since the anaerobic digestion process and the used influent are very similar, data from this installation is used for further calculations.

For every 1000kg of organic waste input, 70kg of biogas, 500kg of compost and 230kg of wastewater is produced. Also 30kg compost that require post treatment, 120kg of vaporised water and 50kg of non-recyclables. A schematic mass and energy balance for the Wildemanbuurt after installation of a Biocel anaerobic digestion plant including post-treatment is presented in figure 7.

The installation in Lelystad uses 14 reactors of 720m3 each, to treat the 50,000 ton every year. Based on this, a 80,6 m3 reactor could be sufficient to treat the 399,8 ton in the Wildemanbuurt. When using the same height × length × depth proportions as in Lelystad, that results in reactor dimensions of 2.9 × 2.9 × 9.6 (h × l × d). This means a surface area of approximately 28m2. The reactor in Lelystad has a retention time of 21 days (Ten Brummeler, 2000). For the Wildemanbuurt this means that either every 3 weeks the organic waste is collected or the waste has to be stored before it enters the digester. Another option is to work with multiple smaller reactors to increase the collection interval.

Energetic value

Figure 7 shows that the Wildemanbuurt could produce 28 ton of biogas per year out of its organic waste. As

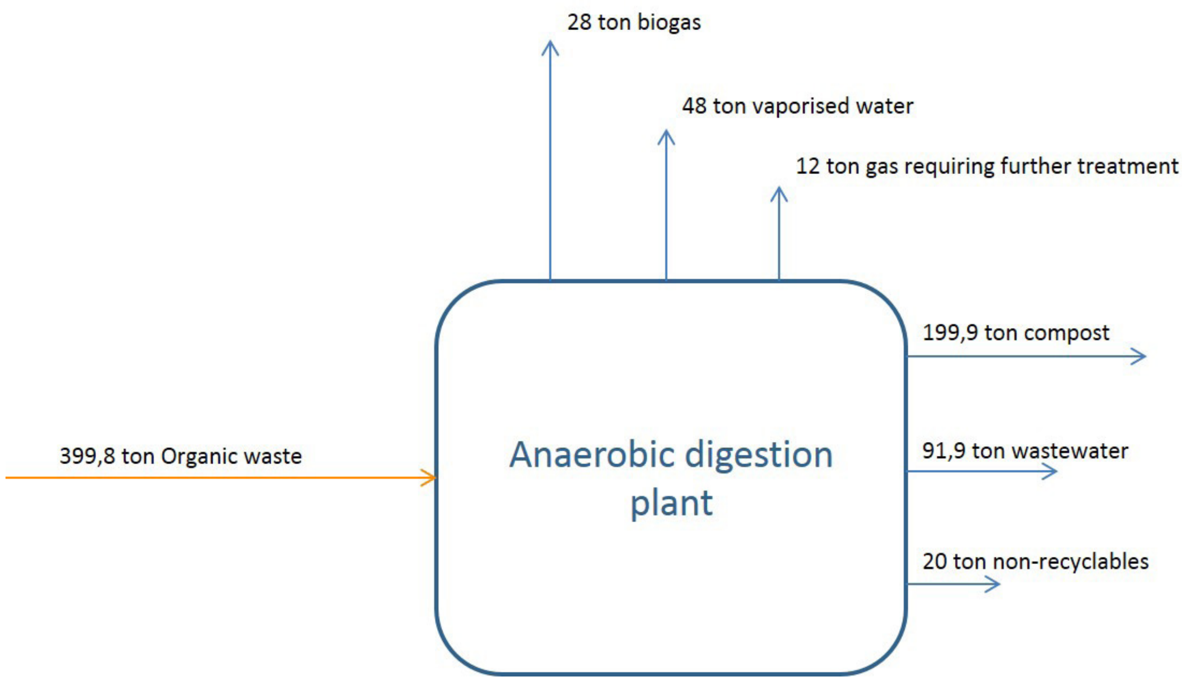


Figure 7. Schematic overview of the Biocel anaerobic digestion process including post-treatment for the Wildemanbuurt per year. Adapted from Ten Brummeler (2000).

mentioned before, biogas exists for 50-75% out of methane (CH_4), for 20-45% out of carbon dioxide (CO_2) and for 2-7% out of water (de Graaf & Fendler, 2010). Biogas has a density of approximately 1.2 kg/m3 (Balat & Balat, 2009; Jørgensen, 2009; Rao, Baral, Dey, & Mutnuri, 2010). Thus, the Wildemanbuurt can produce (28 *1000)/1.2 = 23.333,3 m3 biogas per year with the biocel anaerobic digestion process.

The caloric value of a cubic meter of biogas in literature ranges from 19,5 MJ/m3 to 27.2 MJ/m3 (Ali Shah et al., 2014; De Wilde et al., 2014; Muzenda, 2014; Verma, 2002; R. Zhang et al., 2007). On average a cubic meter of biogas contains 23MJ/m3. This means, the annual waste flow in the Wildemanbuurt has a theoretical average caloric value of 23.333,3 * 23 = 537,6 GJ.

This potential energy can be utilised for production of heat and power, to replace natural gas or as a fuel. Production of heat and power is prevailing and done in a combined heat and power plant (CHP). Figure 8 shows a mass and energy balance of the Wildemanbuurt after implementation of a CHP. Under optimal conditions, CHPs can reach an efficiency of 85-90% (Deublein & Steinhauser, 2008). The combustion of the biogas produces electricity and heat. Up to 30% of the energy is transformed into electricity, up to 60% of the energy is transformed into heat and 10% is lost (Seifried & Witzel, 2010). For the Wildemanbuurt this means an electricity production of 537,6 * 0,3 = 161,3 GJ per year. This corresponds to 44800 kWh, the electricity demand of 20 households in Amsterdam (CBS, 2016b). Also, 536,6 * 0,6 = 322,6 GJ of heat is produced, this corresponds to the spatial heating and warm water demand of 9 average Dutch households (Milieu Centraal, n.d.). Since data of electricity consumption of the Wildemanbuurt and data of the heat consumption for Amsterdam or the Wildemanbuurt is lacking, general data of consumption in Amsterdam and The Netherlands is used.

In order to replace natural gas, or to be used as transportation fuel, biogas needs to be upgraded to biomethane. This upgrade requires a cleaning and an enrichment of the methane content (Ryckebosch, Drouillon, & Vervaeren, 2011). The methane content is increased from 50-75% in biogas to 95-97% in biomethane (de Mes et al., 2003; Ryckebosch et al., 2011). Increasing the methane content is done by removal of CO_2. Based on the methane content, to produce 1 cubic meter of natural gas quality biomethane, 1,536 cubic meter of biogas is needed. So, the total biomethane production of the Wildemanbuurt could be 23.333,3/1.536 = 15.190,95 m3. Over the years 2008-2014 a household in Amsterdam had an average gas consumption of 870 m3 (CBS, 2016b). Based on this, the anaerobic digester in the Wildemanbuurt could provide gas for almost 17 households. Again, since data of the gas consumption of the Wildemanbuurt is lacking, data of the gas consumption in Amsterdam in general is used.

It is important to mention that there are several aspects of the anaerobic digestion process that require energy. For example, equipment for temperature control, mixing and pre-treatment, pumps, post-treatment of compost, waste water and non-recyclables. To lower the plant operation costs, the heat produced by the CHP is often used for heating the digester or drying the digestate (Braun, 2007; Monnet, 2003; Zupančič, Uranjek-Ževart, & Roš, 2008). Literature states that 20-50% of the energy in biogas is used for plant operation (de Mes et al., 2003). In order to have a net energy production, the energy required for plant operation have to be subtracted from the energetic value of the produced biogas. Table 8 presents the number vof households that can be provided with electricity and gas if a CHP is used to produce electricity and heat out of the biogas.

Table 8 Electricity and heat production by anaerobic digestion of organic waste in the Wildemanbuurt per year.

	Number of households provided		
Type of energy	0% of energy produced required for plant operation	20% of energy produced required for plant operation	50% of energy produced required for plant operation
Electricity[1]	20	16	10
Heat[2]	9	7	5

[1] Based on electricity demand in Amsterdam (CBS, 2016b).
[2] Based on heat demand in The Netherlands (Milieu Centraal, n.d.).

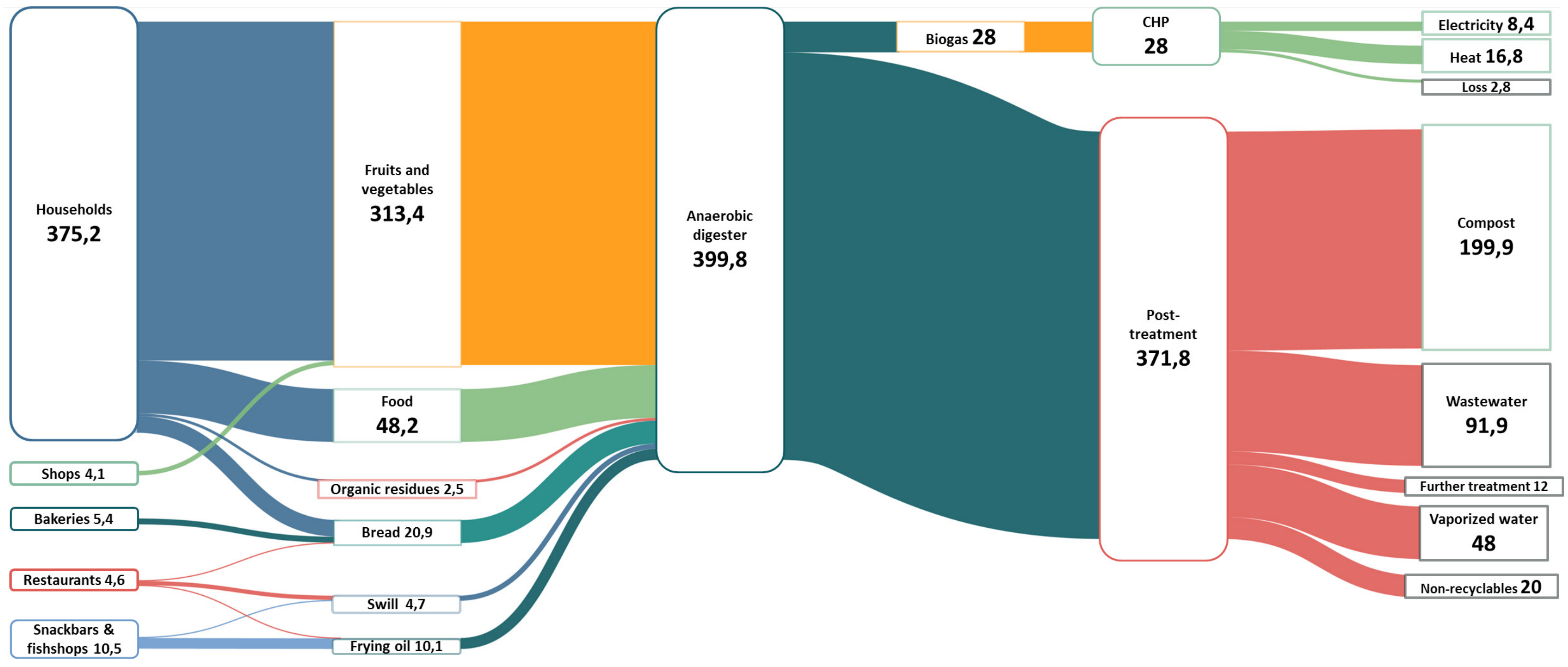


Figure 8. Sankey diagram of anaerobic digestion of organic waste and electricity and heat production using a CHP in the Wildemanbuurt in ton per year

Table 9 presents the number of households that can be provided with gas if the biogas is upgraded. Both tables take into account the scenario that a maximum of 50% of the produced energy, the scenario that 20% of the produced energy and the scenario that none of the produced is used for plant operation.

As mentioned in the introduction, the Wildemanbuurt exits of approximately 2400 households. In the scenario when 50% of the energy produced is required for plant operation, anaerobic digestion of organic waste can provide electricity for 0,4% of the households and heat for 0,2% of the households or natural gas equivalent for 0,4% of the households, per year. In the scenario when 20% of the energy produced is required for plant operation, these values are 0,7%, 0,3% and 0,6% respectively. In the scenario when none of the energy is used for plant operation, these values are 0,8%, 0,4% and 0,7% respectively.

Circular flow diagram

After implementation of the anaerobic digester in the Wildemanbuurt, the waste should be separately collected. The organic waste will be transformed into biogas and digestate in the anaerobic digester. Implementation of a CHP is required to produce electricity and heat. Alternatively, implementation of an gas upgrading facility is required to upgrade the biogas to natural gas quality. Implementation of post-treatment is required to transform the digestate into valuable fertiliser. The energy can flow from the CHP or upgrading facility to the suppliers of the organic waste. The fertiliser can be sold and used for agricultural purposes. This transforms the an output (waste) into an input (energy and nutrients), this makes the system more circular. Figure 9 on the next page shows a schematic overview of the Wildemanbuurt after implementation of an anaerobic digester, a post-treatment facility and a CHP or gas upgrading facility. The sizes of the arrows are not in proportion to the acutal size of the flows. The blue arrow going into the Wildemanbuurt box represents all the inputs entering the neighbourhood. On a larger scale an arrow can be drawn from ' Agriculture' to 'Wildemanbuurt'. This arrow represents inputs grown on nutrients from the fertiliser produced by the post-treatment of the anaerobic digestion of the organic waste of the Wildemanbuurt.

Table 9 Natural gas equivalent production by anaerobic digestion of organic waste in the Wildemanbuurt per year.

Type of energy	Number of households provided 0% of energy produced required for plant operation	20% of energy produced required for plant operation	50% of energy produced required for plant operation
Natural gas equivalent[1]	17	14	9

[1] Based on gas demand in Amsterdam (CBS, 2016b)

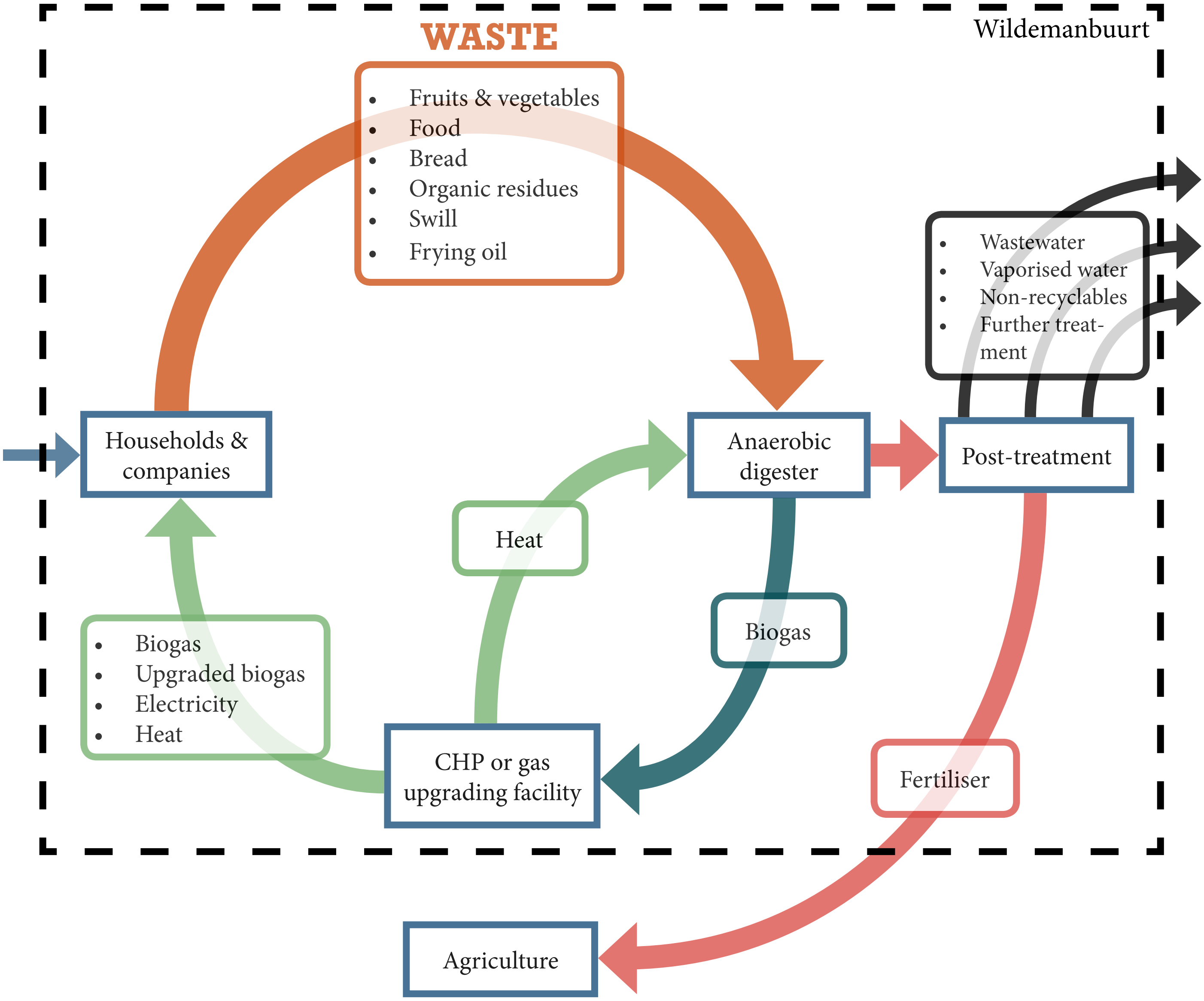


Figure 9. Schematic overview of how anaerobic digestion makes the Wildemanbuurt more circular. Sizes of the arrows are not in proportion to the actual size of the flows.

6. SUSTAINABILITY CRITERIA

The second part of this research has as aim to investigate what determines the optimal scale for anaerobic digestion in the case study area. In order to do this, this chapter aims to define criteria that can be used to assess the contribution of an anaerobic digestion system to the sustainability of a the neighbourhood or a city. These criteria are bundled in a multi-criteria analysis (MCA) which is presented in this chapter and used to assess the sustainability of anaerobic digestion on different scales, in the next chapter.

The criteria have to be formulated carefully since the selected criteria partially decide the outcome of the analysis. (Troldborg, Heslop, & Hough, 2014). The challenge is to formulate criteria that actually cover all aspects that define the sustainability of anaerobic digestion. How the criteria are formulated goes along with the definition of sustainability that is used. To formulate a definition, the first paragraph of this chapter discusses in short the definition according to literature. Next, the definition according to the municipality of Amsterdam as described in the methodology, is discussed. With a clear definition in mind, a set of criteria to assess sustainability of anaerobic digestion is presented to conclude this chapter.

Definition of sustainability

Definition according to literature

An often used description when defining sustainability is the one described in the 'Brundtland-report' written by the World Commission on Environment and Development (WCED, 1987). This commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987 p.41). Over the years that followed, sustainability became a popular concept in different fields of science and society which made the definition sometimes vague (Santillo, 2007). Even though there are a lot of definitions and multiple interpretations of the concept, many of them are based on three pillars; environmental, social and economic aspects (Pope, Annandale, & Morrison-Saunders, 2004). Next to these three aspects, Valentin and Spangenberg (2000) propose institutional aspects as fourth operational pillar to achieve sustainability.

Sustainability according to the municipality

As mentioned in the methodology, the municipality of Amsterdam has several policy documents describing the city's view on sustainability. Considering the five pathways as described in Gemeente Amsterdam (2015b), this research is related to the first pathway (renewable energy) and the third pathway (circular economy). Anaerobic digestion can contribute to the target for 2020 to produce 20% more renewable energy per capita compared to 2013. The municipality focusses, next to other things, on deriving heat from more renewable sources. Anaerobic digestion and especially reusing and recycling the nutrients in the digestate contribute to the circular economy in Amsterdam.

Multi-criteria analysis

The goal of this research is to assess anaerobic digestion of organic waste on neighbourhood and city scale in Amsterdam on local and global, short-term and long-term sustainability. In order to do so, sustainability assessment criteria are identified and a multi-criteria analysis is performed.

This study aims to work with a definition of sustainability strongly based on literature while relevant and useful for Amsterdam and the Wildemanbuurt. At the same time the definition and the criteria that follow it, should be useful when assessing an anaerobic digestion system. Considering the scope of this study, the environmental, economic and institutional aspects of sustainability are taken into account. Within this study, the institutional aspect result in operational aspects. The mere social side of sustainability is considered out of the scope of this research. However, the human side of the implementation of a technology is covered by the operational criteria.

Seghezzo, (2004) presented an overview of studies assessing the feasibility and sustainability of environmental technologies in general, sanitation technologies and sewage treatment systems. The criteria or categories used in some these studies are listed below:

Alaerts, Veenstra, Bentvelsen, & van Duijl (1990) - Feasibility of a wastewater treatment system
- Environmental feasibility;
- Reliability;
- Institutional and technical manageability;
- Cost and financial sustainability;
- Possible application in re-use schemes

Dunmade (2002) - Sustainabilty of implementation of a foreign technology in a developing country
- Technical criteria
- Economic criteria
- Environmental criteria
- Socio-political criteria

Lettinga (2001) - Long term sustainability prescriptions for environmental technologies
- Little use of resources or energy
- Production of resources or energy
- Efficiency and durability
- Flexibility in terms of scale of application
- Simplicity in construction, operation and maintenance

Adaptation of the above mentioned criteria for anaerobic digestion of organic waste on neighbourhood and city scale in Amsterdam resulted in eight indicators divided over three criteria. The criteria and indicators are presented in table 10.

Environmental aspects

Energy production

Energy production by anaerobic digestion of the organic waste in Amsterdam is a source of renewable energy. The combustion of methane produced by anaerobic digestion produces no nett CO2 (Jingura & Matengaifa, 2009). Organic matter takes up as much CO2 while growing, as is emitted to the atmosphere when burning biogas. Biogas can be used to produce heat, steam, electricity, hydrogen, ethanol, methanol and methane (Chynoweth, Owens, & Legrand, 2000). By using biogas to produce energy, less conventional energy sources are needed. Therefore, the more biogas is produced, the more CO¬2 emissions are prevented.

Energy production can be measured in absolute energy production in cubic meters of biogas per year. However, to compare the anaerobic digestion systems of both scales it is also relevant to discuss the relative biogas production per ton organic waste. Also the form of energy the

Table 10 Criteria and indicators used to assess the sustainability of anaerobic digestion in Amsterdam on city and neighbourhood scale. Adapted from Alaerts et al. (1990), Lettinga (2001) and Seghezzo (2004).

Criteria	Indicators	Description[1]
Environmental aspects	Energy production	Biogas production by the anaerobic digester and efficiency of the conversion of biogas to electricity and heat or natural gas.
	Energy consumption	Energy demand for plant operation. For example, equipment for temperature control, pre-treatment and the post-treatment of compost, wastewater and non-recyclables.
	Nutrient recovery	Ability to facilitate recovery, reuse or recycling of nutrients available in the digestate.
Economic aspects	Investment costs	Costs for construction of the plant, purchase of equipment and land.
	Running costs	Regular investments, maintenance and labour costs.
	Sales of outputs	Income from sales of energy and compost.
Operational aspects	Institutional system manageability	Institutions, politics and policy required for system operation.
	Technological system manageability	Hardware and software (skills and knowledge) required for system operation.

[1] Full description in text

biogas is transformed into, is relevant. The different forms of energy can serve different purposes and the transformation processes have different efficiencies.

Energy consumption

Energy consumption indicates the amount of required for plant operation. One anaerobic digestion plant can have a higher and more efficient energy production than another plant, but if the energy demand for the first plant is relatively high, the net energy production can turn out higher for the plant with lower and less efficient energy production. Energy is required by equipment for temperature control, pumps, pre-treatment and post-treatment of compost, waste water and non-recyclables.

Nutrient recovery

Third indicator for environmental sustainability is the ability of an anaerobic digestion installation to facilitate recovery, reuse or recycling of nutrients that are available in the organic waste and in the digestate. Nutrients like phosphorous are essential for food production. Currently, most of the phosphorous used for agricultural purposes comes from one of the few phosphate mines around the world. While the demand for phosphorous increases, the easy accessible phosphate deposits are decreasing (Neset & Cordell, 2012). The digestate of anaerobic digestion of organic waste is identified as an important nutrient source and a sustainable substitute for conventional fertiliser (Vaneeckhaute et al., 2013).

Economic aspects

Investment costs

Investment costs indicate the amount of money required to construct and set up the installation. This includes costs for construction, equipment and land. It includes all the investments required to get the installation on a stable production level. Investment costs are expressed in investment costs divided by the lifetime of the plant. Thereby, high investment costs can be justified by a high installation life time.

Running costs

The second economic criterion indicates the investment required to keep the system running. This includes all the regular investments, maintenance costs and labour costs. Running costs are expressed in costs per ton of organic waste digested.

Sales of outputs

Energy pricing strongly determines the economic feasibility of an anaerobic digestion project (Debruyn, House, & Rodenburg, 2006; Pan et al., 2015). Over the past 10 years the average price for energy increased with 2,4%. The gas price increased with 18% while the price for electricity decreased with 19% (CBS, 2016). Therefore, the sales of the outputs can differ per installation because the prices of different energy forms differ.

As mentioned before, the demand for nutrients is increasing while the supply is decreasing. Consequently, the nutrient prices rise. Therefore, the possibility to reuse the digestate from the anaerobic digestion process is essential for the economic feasibility (de Mes et al., 2003).

Operational aspects

Institutional system manageability

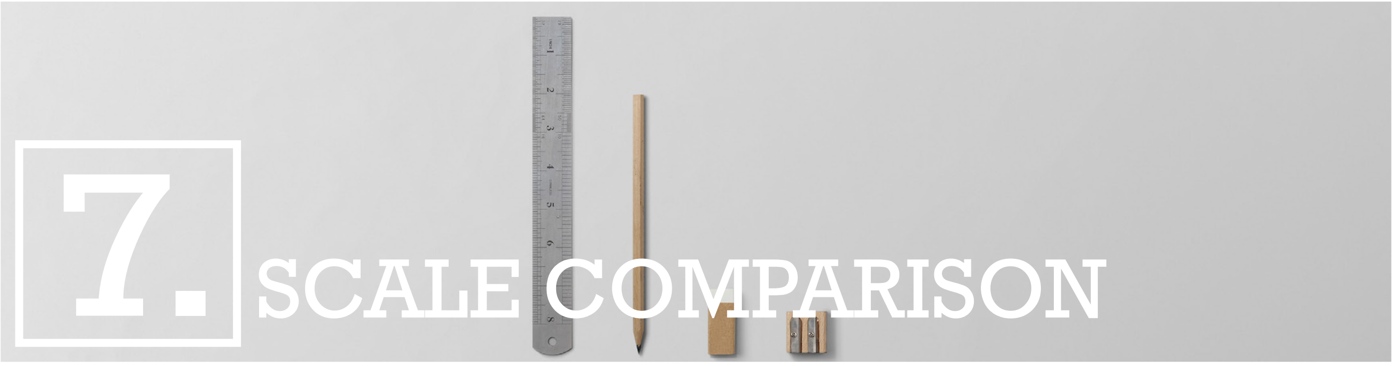
This indicator aims to assess the institutional, political and societal aspects of anaerobic digestion of organic waste. Resources and authority are required to plan, construct and maintain an anaerobic digestion installation. Also, some technologies or scales of operation can be preferred over others based on (local) subjective reasons (Seghezzo, 2004).

Technological system manageability

Technology in this context consists of hardware and software. Hardware is understood as the equipment and machinery, software as the skills and knowledge to develop, produce and use the hardware (Weaver, 2000). This indicator assesses the complexity of operation and maintenance of the installation. It also indicates the dependency on and local availability of software like skills and knowledge, and hardware like infrastructure and spare parts (Dunmade, 2002).

Scoring and weighting

The method for scoring and assigning relative importance used is a simplified version of the method as described in Seghezzo (2004). Per scale, each indicator is scored. Scores are assigned based on literature and assumptions. To simplify the procedure, five different scores can be assigned; 0, 25, 50, 75, 100. According to the contribution of a scale to an indicator, the scale receives a score between 0 (lowest contribution) and 100 (highest contribution) for this indicator. This procedure repeats itself for each scale, for every indicator. The scores, with explanation, are presented in the next chapter. The criteria as well as the indicators can also be assigned a relative weight. By weighting the criteria and indicator the relative importance of a criterion or indicator on a certain scale can be accounted for in the calculation of the overall sustainability.



7. SCALE COMPARISON

This research investigates to what extent anaerobic digestion can contribute to a more sustainable city. Increasing or decreasing the scale offers possibilities as well as challenges. In this chapter, the criteria and indicators as presented in the previous chapter are used to assess the sustainability of anaerobic digestion on city scale and anaerobic digestion in the Wildemanbuurt.

This chapter will compare anaerobic digestion on neighbourhood scale with anaerobic digestion on city scale. Essentially the comparison is between a decentral and a central system. Similar to wastewater systems, a central waste system on city scale requires an infrastructure to collect and transport the waste. It is treated in a central treatment facility and it requires transportation of the waste and biogas (Hophmayer-Tokich, 2006). In a decentralised system, as projected for the Wildemanbuurt, the waste collection and anaerobic digestion process happen close to the point of waste generation.

In the paragraphs that follow, both scales are scored for every indicator. Next, weights are assessed to the criteria and indicators. The results of the sustainability assessment are presented in the last paragraph of this chapter.

Scores

The scores per criteria are presented in table 11. The explanation behind the scores is presented in the text.

Environmental aspects

Energy production

Anaerobic digestion, regardless of the scale, can help to achieve the goals set by Amsterdam regarding renewable energy production. City scale anaerobic digestion has a higher absolute yield than neighbourhood scale because of the larger capacity. Considering relative yield of biogas per unit of feedstock, some remarks can be made for both scales.

1. Type of anaerobic digester

It are mainly operational aspects that lead to the recommendation of an one-phase mesophilic batch reactor with dry influent for the Wildemanbuurt. These operational aspects are different on a city scale. Therefore, a different system could be more suitable for anaerobic digestion on city scale, leading to a different relative biogas production per ton of organic waste digested.

Table 11 Sustainability scores per indicator of anaerobic digestion on city and neighbourhood scale

Criteria	Indicator	City scale score	Neighbourhood scale score
Environmental aspects	Energy production	100	75
	Energy consumption	75	75
	Nutrient recovery	75	100
Economic aspects	Investment costs	50	75
	Running costs	75	75
	Sales of outputs	75	75
Operational aspects	Institutional system manageability	75	50
	Technical system manageability	100	50

Firstly, on neighbourhood scale it was assumed not beneficial to invest in extensive pre-treatment and mixing equipment (Li, 2015; Muzenda, 2014). On a larger scale however, it can become economically feasible to install this equipment. This equipment makes it possible to have a continuous process instead of a batch process. Thereby the methane yield can increase with up to 20% and also the required reactor volume reduces (Arsova et al., 2010; De Wilde et al., 2014).

Next to that, based on the assumption that on city scale there is more expertise, money and equipment available, a two-phase digestion system can be installed. Two-phase digesters have higher investment and operational costs (De Baere & Mattheeuws, 2013). Also, two-phase systems are more difficult to operate than one-phase systems (Li, 2015). However, two-phase systems can be installed to minimise the retention time and maximise the yield (Ostrem & Themelis, 2004).

Lastly, as mentioned before, the process speed and gas production can increase when the process temperature increases (Environment Canada, 2013). To successfully run an anaerobic digestion process at a higher temperature, the environmental conditions have to be kept constant. Even a small fluctuation in temperature can cause trouble for a thermophilic process (Li, 2015). It is assumed that on a city scale, more than on a neighbourhood scale, knowledge and equipment to control the parameters of a reactor are available or can be purchased. Based on that, if a thermophilic city scale installation can be kept at a constant high temperature, the yield will be higher than on a mesophilic neighbourhood scale.

Concluding, a city scale digester can, in theory, reach a higher relative yield than a neighbourhood scale digester, based on the above mentioned arguments. However, it is important to keep in mind that to achieve this higher yield, investment of capital and knowledge is required. The theoretical yield and actual yield will differ. To what extent the theoretical yield is transformed into actual yield depends on the possibility and willingness to invest capital and knowledge.

2. Energy infrastructure

Considering an installation with an anaerobic digester and a combined heat and power plant (CHP), a main driver for energy loss is the distribution of electricity, gas and heat. To minimise the losses, the reactor should be placed close to the CHP and the CHP close the heat demand (Fraker, 2012). It can be assumed that on neighbourhood scale the distances are smaller. If neighbourhood planning allow it, the digester and CHP can be placed close to each other, and close to the waste supply and heat demand sources. Burger (2016) explains that the locations of energy sources are shifting from central packages of oil, gas and coal towards renewable energy sources less bound to a geographical location. In line with this, she states that a vandalism-proof biogas installation with CHP could function in the Wildemanbuurt (Burger, 2016). However, storage and processing of organic waste in a biocel anaerobic digester causes odour issues (Ten Brummeler, 2000). Next to that, storage of biogas in a residential area can cause safety issues. Therefore, even if the neighbourhood planning allows it, it is the question whether legislation and local community allow the construction of an anaerobic digestion plant in a residential area.

On city scale however, the volume of the energy flows are bigger and the reactors and CHP larger. Therefore it might be more difficult to place reactors and CHP's close to the producers of waste and consumers of electricity and heat without causing nuisance. Based on this, the distances are longer so the losses can be higher on city scale. However, by placing the installation outside of residential areas, other heat demands rather than district heating can be located close to the installation. Next to that, by placing the installation outside of residential areas, the odour and biogas storage are considered less of an issue.

As mentioned before, it is possible to upgrade the biogas to reach a higher methane content. The upgraded biogas can flow into the existing gas grid. It has to be investigated whether investing in equipment for upgrading the gas is feasible on neighbourhood scale. Also, it has to be investigated whether policy and law allow a neighbourhood digester to deliver gas to local households or to the grid. After upgrading the biogas to biomethane it can also be used as biofuel (Ryckebosch et al., 2011). This might have to be stored before it is used. Again, safety measurements might have to be taken to be allowed to store biofuel in an urban area.

Concluding, on neighbourhood scale, less infrastructure is required which lowers the energy losses. However, nuisance and safety issues have to be tackled on neighbourhood scale. On city scale, more infrastructure is required to deliver the energy to the waste suppliers. However, other sources of energy demand can be nearby and nuisance and safety are considered less of an issue.

Energy consumption

The second indicator for environmental sustainability is the energy required for running the anaerobic digestion installation. The energy required for plant operation is subtracted from the energy production to get a net energy production.

It is assumed that a city scale installation uses more equipment, for example for mixing, heating and continuous feeding. Therefore it can be assumed that a city scale installation has a high energy demand (de Graaf & Fendler, 2010; De Wilde et al., 2014). Case specific balance has to be found between increase in energy required for plant operation and increase in energy production. De Mes et al., (2003) state that energy demand for plant operation depends on climate and system design. The climate conditions can be considered the same on city scale as for the Wildemanbuurt. Because of more financial and technological resources, it is assumed that on city scale the system can be designed more efficient. Therefore, the relative energy consumption per ton of organic waste digested, is considered lower on city scale. However, the described digester for the Wildemanbuurt is a rather simple installation. Therefore the energy demand for this digester is assumed to be relatively low.

Nutrient recovery

The last indicator for environmental sustainability is the ability of an anaerobic digestion installation to facilitate recovery, reuse or recycling of nutrients. As mentioned in the methodology, on city scale the organic waste will be separated from other waste at the plant by a sorting installation. The heavy metal content in digestate from mechanically separated organic waste is higher than in the digestate of source separated organic waste (de Mes et al., 2003). Therefore, the digestate from the installation on neighbourhood scale can comply with the standards for digestate usage more easily than the digestate of the city scale installation.

Economic aspects

Investment costs

Economy of scale is a relevant financial concept when considering variation of technology costs over scale. Economy of scale looks at the change in average costs of production of a fixed commodity on a fixed timespan at different rates of output (Silberston, 1972). For anaerobic digestion this means, how do the average costs of the production of, for example, 1m3 of biogas per day, change when the total output (m3 of biogas) of the plant changes. It is not simply the case that when the size of an anaerobic digester increases, the average costs per output decrease. Large scale projects might encounter significant higher costs for developmental and legislative work. When evaluating the current investment costs, it is essential to take future expenses and the lifetime of an anaerobic digester into consideration to be able to compare the present value of future costs and benefits (Cleaver, 2004; Silberston, 1972). Economies of scale is present for as long as the total present investment costs, including research and infrastructural costs, divided by the biogas production, is decreasing when the scale increases. Studying the theory of economies of scale shows that in many cases the average costs of a technology have a tendency to decrease when the scale increases (Anderton, 2000). Applied to biogas plants, there are studies that claim that when the plant size increases, the investment costs per produced kWh decrease (Walla & Schneeberger, 2008). Another study claims the same trend for CHP's (Itron, 2011). At some point the total costs increase with the same rate as the average costs. At this point there is a constant return to scale (Cleaver, 2004). Depending on the nature of the business and product, at some point increasing the capacity might lead to increased difficulties and complexities. In case of anaerobic digestion, at some point extra equipment is required. For example, the shift from a batch process to a continuous process increases the costs (de Graaf & Fendler, 2010). After the point of constant returns to scale, the average costs per output can increase again (Anderton, 2000; Cleaver, 2004). What the influence of economies of scale or diseconomies of scale is, highly depends on the type of industry and on what is produced. In the case of anaerobic digestion, the increase in investment costs when increasing the scale can be driven by developmental and infrastructural investments. At some point in size between a household scale digester and non-defined larger scale digester, the extra investment costs are no longer beneficial considering the increase in average costs. This point, the optimal size for an anaerobic digester purely based on investment costs, is uncertain and requires further research.

In general, anaerobic digestion installation costs are low and require less land than conventional organic waste treatment systems (de Mes et al., 2003). The installations on both scales require standard equipment to weigh and receive the waste ,equipment for pre-treatment, storage capacity, reactors, biogas storage, energy transformation and distribution equipment post-treatment equipment (Moriarty, 2013). On a city scale, also equipment for waste separation is required.

Concluding, a city scale anaerobic digestion installation requires a higher investment than a neighbourhood scale anaerobic digestion installation. However, this can be justified by a long lifetime or a high energy production.

Anaerobic digestion on neighbourhood scale has lower investment costs because of the relative simple installation.

Running costs

Next to investment costs, running costs is another element of economic sustainability. The limited literature available on running costs, state that it varies from €40-€50 per ton to around 75€ per ton to annually 10-15% of the investment costs (de Mes et al., 2003; Heeb, 2009; Moriarty, 2013). Economic operation of an anaerobic digester is only achieved by optimised system operation and limited crashes (Debruyn et al., 2006). Optimal system operation with limited crashes requires skills and knowledge for maintenance and control. It is assumed that the anaerobic digestion process on city scale runs more stable with less crashes due to more skills and knowledge available. Based on this, the running costs per unit of output should be lower on city scale. Contrary, the relative simple installation in the Wildemanbuurt has less costs for energy and labour to operate the plant.

Sales of outputs

On city scale, energy is produced more efficiently but the digestate requires more post-treatment. On neighbourhood scale, the digestate requires less post-treatment but the energy production is less efficient. Energy and fertiliser pricing are considered the same. Therefore, both scales receive the same score on this indicator.

Operational aspects

Institutional system manageability

Public participation is crucial for anaerobic digestion on neighbourhood scale. Without people separating their waste, there is no organic waste to digest. Currently there are waste collection points for glass and plastic in the Wildemanbuurt. Previous research in the Wildemanbuurt showed that people hardly use these containers for separate collection of glass or plastic (Blom, Dekkers, Hiemstra, Schreefel, & Wester, 2016). On the other hand, some companies in the Wildemanbuurt are already used to separating their waste. However, the volume of companies' waste is very small compared to the volume of household waste. Separate collection of organic waste is difficult for households in Amsterdam, states Van Zoelen (2016). Main argument for people to not separate waste is smell it produces and lack of space for storage in small apartments (van Zoelen, 2016).

Politics and policy have influence on the construction and operation of an anaerobic digestion plant. Economic analysis of some anaerobic digestion projects showed positive net present values only for projects with subsidy (Gebrezgabher, Meuwissen, Prins, & Lansink, 2010). After investing in the waste sorting installation of the AEB (AEB, 2016), the question is whether the municipality wants to subsidise or invest in an anaerobic digestion plant in the Wildemanbuurt. In general, the policy on renewable energy in The Netherlands is criticised for being too unstable (van Rooijen & van Wees, 2006).

Technological system manageability

It can be seen that when the installation's capacity and biogas yield increase, the difficulty of system operation increases. Moreover, when an installation's treatment capacity increases the need for equipment, infrastructure and organisational structure increases. Therefore, due to the advanced installation, anaerobic digestion on city scale requires more hardware (equipment) and software (knowledge and skills to use and maintain the equipment). As part of this research the author is member of a 'WhatsApp' group that takes care of the maintenance and control of the bread digester in the Wildemanbuurt. The group exists of initiators from the Lucas Community and The Beach, the manufacturer of the digester and other parties involved, including local residents. Updates of temperature, pH and biogas yield are reported in this group. Based on the update of these parameters it is decided if and how the anaerobic digestion process should be adjusted. This kind of community controlled technology management seems successful for a neighbourhood scale bread digester. The neighbourhood aims at setting up an energy cooperation around the new digester. This energy cooperation should be responsible for the energy production and distribution. Whether a similar kind of management is successful in running a neighbourhood scale digester is yet unclear considering it has not been set up yet.

Considering city scale, some organisational changes are expected as well. Currently there is already a city-wide waste collection and treatment system in function. If the system is expanded with a sorting installation and an anaerobic digestion, mainly the practice on the treatment site change. Arrangement of a biogas, electricity and heat or fuel distribution system requires extra organisational and technological management. However, this is already partially in place since the AEB is used to transform biogas from the wastewater treatment company into electricity and heat (Rooijmans, 2013).

As mentioned before, the technological manageability changes over scale. The biogas produced by the bread digester that is currently in use in the Wildemanbuurt is stored next to the digester. Every once in a while a cooking event takes place where residents gather around the digester and cook on the biogas. When the bread digester is upgraded to a general organic waste digester, the required storage capacity will increase. Therefore, new equipment for storage, energy conversion and energy distribution is needed. This equipment requires skills to operate which could make managing the system more difficult.

Concluding, anaerobic digestion on city scale requires more equipment and skills and knowledge to run and maintain the equipment due to the more advanced equipment. However, both hardware and software are already partially available at the AEB. Hardware and software required for anaerobic digestion is assumed more easily accessible on city scale than in the Wildemanbuurt.

Weights

Weights are assigned to the criteria and indicators. The weights of the criteria together and the weights of the indicator together, both add up to 1.0. A weight represents the relative importance of a criterion or indicator. The assignment of weights is based on subjective estimations and assumptions. For example, a certain can value the importance of the economic aspects higher than the importance of the environmental aspect. Another example, people in the Wildemanbuurt can value the relative importance of investment costs higher than the relative importance of nutrient recovery. It is important to mention here that in order to use this sustainability assessment for decision making, a representative set of weights has to be formulated. Relevant stakeholders and experts together can formulate a set of weights that is more representative. In this case relevant people to invite can be, for example, representatives of the Wildemanbuurt, the municipality, anaerobic digestion experts and organic waste experts. However, this method always contains some level of subjectivity, because also the decision who to invite for weighting the criteria is a biased decision. Therefore, when presenting or communicating the results of a MCA it is important to make this subjectivity explicit (Seghezzo, 2004). Table 12 presents a set of normalised weights where every criterion is considered equally important and every indicator per criterion as well.

Sensitivity analysis

Different stakeholders can weigh the criteria differently. It is interesting to investigate how the outcome of the MCA changes in relation to changes in relative importance of the criteria. Therefore, three other sets of weights are formulated. One set of weights with the emphasis on the environment, one set of weights with the emphasis on economy and one set of criteria with the emphasis on operational aspects. These three sets of criteria are presented in table 13.

Table 12 Weights assigned to equally important criteria and indicators

Criteria	Weight	Indicator	Weight
Environmental aspects	0.33	Energy production	0.33
		Energy consumption	0.33
		Nutrient recovery	0.33
Economic aspects	0.33	Investment costs	0.33
		Running costs	0.33
		Sales of outputs	0.33
Operational aspects	0.33	Institutional system manageability	0.5
		Technological system manageability	0.5

Table 13 Sets of weights used for the sensitivity analysis

Set of weights	Weight of environmental aspects	Weight of economic aspects	Weight of operational aspects
Emphasis on environment	0.5	0.25	0.25
Emphasis on economy	0.25	0.5	0.25
Emphasis on operational aspects	0.25	0.25	0.5

Table 14 Weights assigned to criteria and indicators by the author

Criteria	Weight	Indicator	Weight
Environmental aspects	0.4	Energy production	0.5
		Energy consumption	0.2
		Nutrient recovery	0.3
Economic aspects	0.3	Investment costs	0.3
		Running costs	0.3
		Sales of outputs	0.4
Operational aspects	0.3	Institutional system manageability	0.5
		Technological system manageability	0.5

Weights assigned by author

Table 14 presents the weights of the criteria and indicators assigned by the author. Again, it is important to mention here that the assigned values contain a significant level of subjectivity. As mentioned before, prior to implementation of an anaerobic digestion plant on a certain scale, weights have to be assigned by all relevant stakeholders to get representative weights. However, the assigned weights in this study are by no means blind guesses. The weights are assigned based on assumptions and experiences gained while conducting this research. The weights are presented in table 14, the explanation follows in the paragraphs thereafter.

Criteria

Considering anaerobic digestion of organic waste, the criteria environmental aspects was considered the most important. The production of energy as well as the ability to recover nutrients are the main drivers for considering anaerobic digestion. Economic aspects and operational aspects are considered equally important.

Indicators

Considering the environmental aspects of anaerobic digestion, energy production is assumed the most important indicator. Production of biogas is what makes anaerobic digestion a renewable energy source. The more energy produced, the less conventional energy sources required. Second most important indicator is nutrient recovery since the digestate of anaerobic digestion is assumed a sustainable source of nutrients. Least important indicator for environmental sustainability is energy consumption since increased energy consumption strongly relates with increased energy production.

Considering the economic aspects of anaerobic digestion, the sales of the outputs is considered the most important indicator. As mentioned before, electricity pricing and sales of digestate are essential for economic feasibility of an anaerobic digestion plant (de Mes et al., 2003). Investment costs and running costs are considered equally important since both depend on the financial resources of the decision-maker.

Considering the operational aspects of anaerobic digestion, technological system manageability and institutional system manageability are assumed to be equally important. Both are considered equally essential for successful anaerobic digestion on both scales.

Results

This sup-chapter presents the results of the sustainability assessment using 5 types of weights.

- Normalised weights, every criteria is equally important;
- Emphasis on environmental aspects;
- Emphasis on economic aspects;
- Emphasis on operational aspects;
- Criteria assigned by the author.

For every set of weights used, the sustainability assessment showed a higher score for the city scale compared to the neighbourhood scale. For every set of weights used, the city scale scored higher than the neighbourhood scale on the environmental and operational aspects. The Wildemanbuurt scores higher on economic aspects of sustainability regardless of the set of weights used.

Table 15 and figure 10 present the results of the sustainability assessment based on equal importance of the criteria and indicators. Anaerobic digestion of organic waste on city scale receives a higher sustainability score for the environmental aspects and for the operational aspects. Anaerobic digestion on neighbourhood scale scores higher on the economic aspects criterion. When every criteria is assumed equally important, the city scale scores a total of 81,9 and the Wildemanbuurt scores 69,4. Both scales score 52,8 on environmental aspects and economic aspects together. The main reason that city

Table 15 Results of the sustainability assessment based on equal importance of the criteria and indicators

Criteria	Weight	Indicators	Weight	Score city scale	Sustainability city scale	Score Wildeman-buurt	Sustainability Wildeman-buurt
Environmental aspects	0,33	Energy production	0,33	100	11,1	75	8,3
		Energy consumption	0,33	75	11,1	75	8,3
		Nutrient recovery	0,33	75	8,3	100	11,1
Total for criterion					**30,6**		**27,8**
Economic aspects	0,33	Investment costs	0,33	50	5,6	75	8,3
		Running costs	0,33	75	8,3	75	8,3
		Sales of outputs	0,33	75	8,3	75	8,3
Total for criterion					**22,2**		**25,0**
Operational aspects	0,33	Institutional system manageability	0,5	75	12,5	50	8,3
		Technological system manageability	0,5	100	16,7	50	8,3
Total for criterion					**29,2**		**16,7**
Total					**81,9**		**69,4**

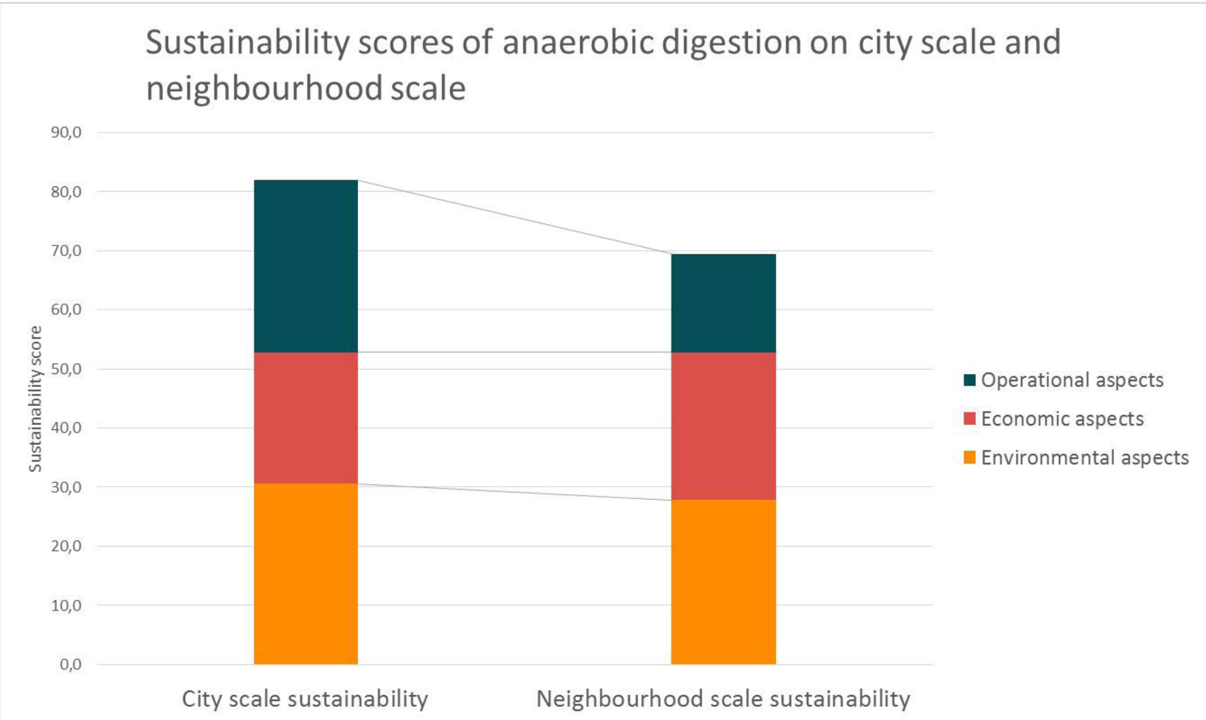


Figure 10. Sustainability scores of anaerobic digestion on city scale and neighbourhood scale based on equal imporatnce of the criteria and indicators

scale has a higher total sustainability score is because of the high score on operational aspects (29,2) compared to the Wildemanbuurt (16,7).

Sensitivity analysis

The results when using the sets of weights described for the sensitivity analysis are presented in table 16and figures 11a-c.

In the case of strong relative importance of any of the criteria, anaerobic digestion scores higher on city scale than on neighbourhood scale. When every criteria is assumed equally important, the city scale scored 81,9. The same scale scores higher when the focus is on environmental aspects (84,4) or on operational aspects (83,3). Compared to the score when the criteria are assumed to be equally important, the city scales lower when the emphasis is on economic aspects (78,1). Considering the neighbourhood scale, it scored 69,4 when all the criteria are assumed to be equally important. With a focus on environmental aspects it scored higher (72,9), with a focus on economic aspects also higher (70,8), with a focus on operational aspects it scored lower (64,6).The highest absolute score (84,4) is assigned to the city scale when the weights with an emphasis on environmental aspects are used. The neighbourhood scale also scores best (72,9) when the weights with an emphasis on environmental aspects are used. The highest relative score (29% higher than neighbourhood scale) is assigned to the city scale when the weights with an emphasis on operational aspects are used.

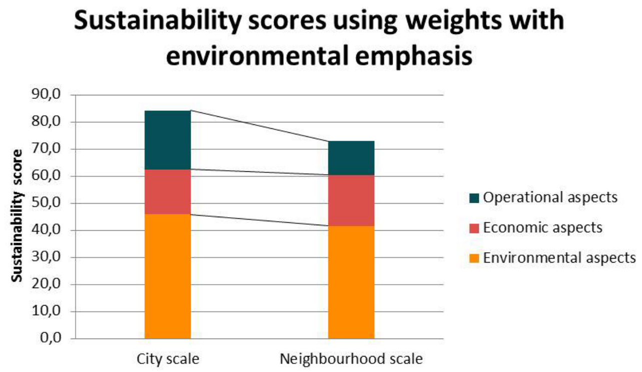


Figure 11a. Sustainability scores using weights with environmental emphasis

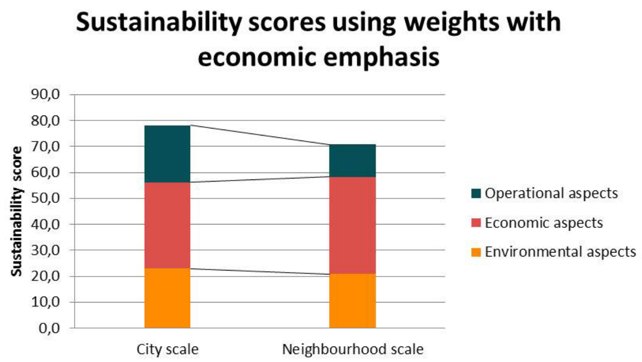


Figure 11b. Sustainability scores using weights with economic emphasis

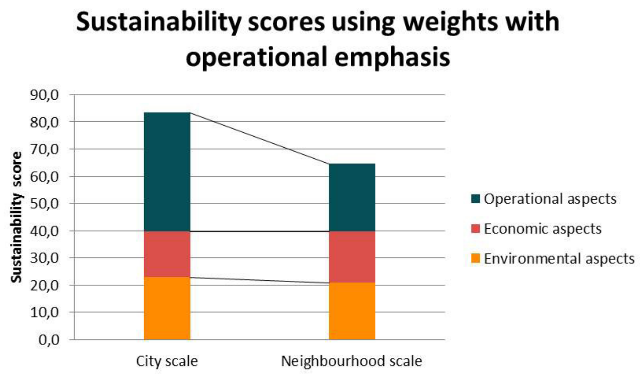


Figure 11c. Sustainability scores using weights with operational emphasis

Table 16 Results of the sustainability assessment using the sets of weights used for the sensitivity analysis

	Emphasis on environment		Emphasis on economy		Emphasis on operational aspects	
Sustainability score	**City scale**	**Neighbourhood scale**	**City scale**	**Neighbour-hood scale**	**City scale**	**Neighbour-hood scale**
Environmental aspects	45,8	41,7	22,9	20,8	22,9	20,8
Economic aspects	16,7	18,8	33,3	37.5	16,7	18,8
Operational aspects	21,9	12,5	21,9	12,5	43,8	25,0
Total	**84,4**	**72,9**	**78,1**	**70,8**	**83,3**	**64,6**

Results weights assigned by author

Table 17 presents the results of the sustainability assessment using the weights assigned by the author.

When the weights assigned by the author are used, city scale anaerobic digestion scores 83,5 and anaerobic digestion in the Wildemanbuurt scores 70,5. Compared to the values when the criteria are assumed equally important, the values differ +1,9% and +1,5% for city scale and neighbourhood scale respectively.

Table 17 Results of the sustainability assessment using the weights assigned by the author

Criteria	Weight	Indicators	Weight	Score city scale	Sustainability city scale	Score Wildeman-buurt	Sustainability Wildeman-buurt
Environmental aspects	0,40	Energy production	0,50	100	20	75	15
		Energy consumption	0,20	75	8	75	6
		Nutrient recovery	0,30	75	9	100	12
Total for criterion					**37**		**33**
Economic aspects	0,30	Investment costs	0,30	50	4,5	75	6,8
		Running costs	0,30	75	6,8	75	6,8
		Sales of outputs	0,40	75	9	75	9
Total for criterion					**20,3**		**25,0**
Operational aspects	0,30	Institutional system manageability	0,5	75	11,3	50	7,5
		Technological system manageability	0,5	100	15	50	7,5
Total for criterion					**26,3**		**15**
Total					**83,5**		**70,5**

8. DISCUSSION

The previous chapters have presented the results of this research. Before conclusions can be drawn out of these results, this chapter will discuss the findings. The aim of this chapter is to critically reflect on the influence of the chosen methodology on the outcome of this research. First the implications of the major findings of this study are discussed. Secondly the findings are put in perspective to current practices and other studies. Thereafter the limitations of this study are discussed. Lastly, suggestions for further research are presented.

Major findings and meaning

The results of this study have shown that anaerobic digestion of the almost 400 ton organic waste per year in the Wildemanbuurt can theoretically produce 28 ton of biogas (23.333 m3) per year. Also, when the Biocel technology is used in combination with post-treatment, almost 200 ton of compost is produced per year ready for agricultural use. This shows that anaerobic digestion of organic waste in the Wildemanbuurt is a possibility to transform outputs (organic waste) into inputs (energy and fertiliser). Considering the need for renewable energy sources, anaerobic digestion of organic waste, as a locally available renewable energy source, can be part of the solution. Next to that, with rising nutrient prices, anaerobic digestion of organic waste can be an economic, locally available, renewable source of nutrients.

The multi-criteria analysis to assess and compare the sustainability of anaerobic digestion of organic waste on two scales showed a higher score for anaerobic digestion on city scale. This means, based on the assessment method and assigned weights and scores used in this study, anaerobic digestion of organic waste on city scale contributes more to the sustainability of Amsterdam than anaerobic digestion on neighbourhood scale. This is supported by the results of the multi-criteria analysis when different sets of weights are used. For every set of weights, city scale scores higher on the environmental and operational criteria, and on the overall sustainability score. Neighbourhood scale scores higher on economic criteria for every set of weights. However, when the set of weights with an emphasis on the economic aspects of sustainability are used, the overall score of city scale is higher. This means that when the stakeholders and experts responsible for assigning the weights assign relatively high weights to one of the criteria, it is most likely that city scale will still score a a higher sustainability score than neighbourhood scale.

Findings in perspective

In this subchapter the main findings or assumptions of this study, are put in perspective to current practices in society or to other studies.

Biocel anaerobic digestion technology

Based on operational and economic considerations, the Biocel anaerobic digestion technology was considered the most appropriate type of digester for the Wildemanbuurt. The theoretical yield of this installation in the Wildemanbuurt was 23.333 m3 of biogas. Due to the simplicity of this installation, the calculated theoretical yield is a low estimation of the potential for the Wildemanbuurt (Miriam van Eekert, personal communication, April 13, 2017). The technology and yield described in this research can be placed into perspective to other technologies by comparing the theoretical yields. Based on a more advanced anaerobic digester and using the potential biogas yields as described by Braun (2007), the theoretical biogas yield is 57.953 m3 per year. Calculations for this are provided in Annex 4. So, in theory the biogas yield can be more than twice as high. This does not make the results of this study worthless, it shows that the potential theoretical yield can be higher when a more advanced anaerobic digestion installation is used.

Anaerobic digestion in comparison to incineration

As mentioned in the introduction, studies claim that anaerobic digestion municipal organic waste is a promising opportunity for combined waste treatment and energy production (Lee et al., 2009; Thenabadu, 2014). From there on, this research investigated how anaerobic digestion on neighbourhood scale looks like and how an optimal scale for anaerobic digestion is determined. How anaerobic digestion performs related to the current waste treatment method, incineration, is discussed here.

As mentioned in before in the methodology, currently most of the organic waste is incinerated by the waste treatment company, Afval Energie Bedrijf (AEB). By incineration of the organic waste the AEB also produces energy. However, by incineration of the organic waste the nutrients present in the waste flow are lost, while by anaerobic digestion of organic waste the nutrients are available for reuse. Next to that, the biogas produced by an anaerobic digester can be converted to many energy forms such as heat, steam, electricity, hydrogen, ethanol and methanol. Therefore it could be considered more useful. Being able to convert to multiple forms could make it easier to store the energy.

Waste hierarchy

In perspective to the waste hierarchy as designed by the European Directive concerning integrated pollution prevention and control (European Parliament Council, 2008), energy recovery through anaerobic digestion is the second least favourable waste treatment option. The waste hierarchy as presented in figure 12 shows that before energy recovery, waste should be prevented, reused or recycled.

However, most of the organic waste is produced during food production and food processing phases, so, mostly before it enters the Wildemanbuurt and partly before it enters Amsterdam. Besides that, nutrients in organic waste that is anaerobically digested are recycled when the digestate is used as fertiliser. This makes anaerobic digestion of organic waste a combination between recycling and energy recovery.

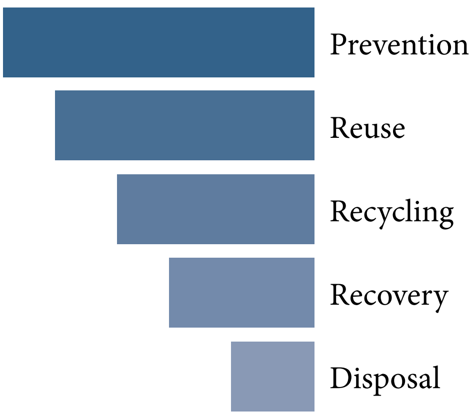


Figure 12. Waste hierarchy, adapted from (European Parliament and Council, 2009)

Share of local energy demand

Lastly, to what extent anaerobic digestion contributes to the sustainability of the Wildemanbuurt is expressed in household energy demand equivalents. As mentioned in chapter five, with a theoretical 50% of the energy produced required for system operation, the anaerobic digester is able to produce gas for nine households. To put this into perspective, this corresponds to 0,4% of the households. The question here is, to what extent a project can be called sustainable. It could be that, with for example energy saving lightbulbs and home insulation, the major steps towards sustainability are already taken. It is also possible that other measures are capable of contributing more to the sustainability. The question whether or not it is worth to invest in a project that produces renewable energy for 0,4% of the households, is up to local decision makers.

Outcome of the multi-criteria analysis

For the multi-criteria (MCA) analysis used in this research, three criteria and eight indicators were formulated to assess the sustainability of anaerobic digestion on different scales. These criteria were based on studies with similar sustainability assessment methods and on the definition of sustainability. In this research, the scores are assigned by the author, with a background in environmental sciences. The assignment of scores and the formulation of criteria are processes that can be unconsciously influenced by the bias of the author. In the MCA used in this research, anaerobic digestion on city scale scored higher than on neighbourhood scale. When the assignment of the scores and the formulation of criteria is done by somebody from a different field of science, the outcome of the sustainability assessment can be different. Therefore, it is important to mention that before the MCA is used as a decision-making tool, the formulation of the criteria and the assignment of scores and weights has to be done by a group of representative stakeholders and experts.

Feasibility

The next part will discuss the feasibility and applicability of the outcomes of this research. It is difficult to predict the success or life time of such a project since there is few long-term experience with digesters in The Netherlands (Gebrezgabher, Meuwissen, Prins, & Lansink, 2010b).

Public participation

The acceptance and successful implementation of a technology or project on any scale strongly depends on local social and societal factors (Rijsberman & Van De Ven, 2000). Different scales and different locations can call for different solutions. As stated by Rijsberman and

Van De Ven (2000), the successful implementation of a technology on a certain scale will, to large extent, depend on the acceptance of local stakeholders.

Separate collection of organic waste in the Wildemanbuurt is essential for the feasibility of neighbourhood scale anaerobic digestion. When the people in the Wildemanbuurt do not separate their waste, there is no organic waste to digest. As mentioned in the scale comparison chapter, people hardly use the containers for separate collection of glass or plastic (Blom et al., 2016). Next to that, Van Zoelen (2016) states the main argument for people in Amsterdam to not separate their waste is the smell and lack of space in small apartments.

It is important to mention here that personal communication during meetings in the neighbourhood showed that people are motivated to make the anaerobic digestion a success. The bread digester that is currently installed in the neighbourhood makes people come together and interact during communal cooking events. Next to that, people want to work towards energy independency and are dissatisfied that the AEB is generating energy out of their waste without compensating them.

Concluding, public participation is essential for the feasibility of anaerobic digestion in the Wildemanbuurt and so far the people in the Wildemanbuurt show motivation to make an anaerobic digestion project successful.

Economic feasibility

It is important to keep in mind that theoretical biogas yield can strongly vary from the actual biogas yield (Environment Canada, 2013). Next to that, over the past 10 years the gas price increased with 18% while the price for electricity decreased with 19% (CBS, 2016a). Fluctuation in energy pricing is an external factor that can be anticipated on at the time of construction. When the project is carried out, technology can be installed so the biogas can be transformed in the, by that time, most profitable form of energy. However, future energy pricing fluctuations can change the economic feasibility of anaerobic digestion installations.

Besides that, local politics and policy can influence the economic feasibility of anaerobic digestion. There are studies that show that economic analysis of anaerobic digestion only has positive net present values for projects with subsidy (Gebrezgabher et al., 2010). After investing in the AEB, the question is whether the municipality wants to subsidise or invest in local anaerobic digestion systems. Next to that, policy on renewable energy in The Netherlands is criticised for being too unstable (van Rooijen & van Wees, 2006). Such an unstable climate could make it difficult to find investors required for carrying out the project. These arguments make the economic feasibility of anaerobic digestion on neighbourhood scale as described in this research questionable.

Limitations

Approach towards the Wildemanbuurt

In the first place, interviews were used to collect neighbourhood specific organic waste data from the companies in the Wildemanbuurt and this data collection strategy has some limitations. The data collected through interviews in this research is assumed to be true. However, the given answers can differ from actual values, for multiple reasons. People can misunderstand the asked questions and people can knowingly or unknowingly give false answers during an interview. In the case this research, the questions and answers had to be translated. By translation, possibly another layer of uncertainty is added. Further research with a different approach can prevent this, as discussed in the next subchapter.

Secondly, this study was designed as a rather explorative feasibility study. Therefore general waste data of the city district Amsterdam Nieuw West were used to formulate qualitative and quantitative characteristics of the organic waste flow in the Wildemanbuurt. Because of the use of this general data, the results of this research can turn out different when waste data specific for the Wildemanbuurt is collected and used for the calculations. Neighbourhood specific organic waste characteristics such as, for example, nutrient and moisture content can be relevant to know before designing a digester.

Lastly, due to the rather technical approach towards the Wildemanbuurt used in this research, the social aspects of anaerobic digestion in the Wildemanbuurt might have been underestimated. As mentioned at the economic feasibility paragraph, personal communication during meetings in the neighbourhood showed that people are motivated to make the anaerobic digestion project in the Wildemanbuurt a success. People their motivations come from distrust in the municipality and large energy companies. Next to that, people are dissatisfied that the AEB is generating energy out of their waste without compensating them. All these arguments are left out of consideration due to the approach used in this research. Whether or not anaerobic digestion in the Wildemanbuurt is the best solution to solve the local dissatisfaction is unclear. It might be valuable to also investigate other options in which the people are compensated for their waste. Other business models could work as well. For example, centralised collection and anaerobic digestion managed by the AEB while people share in the biogas production revenue could be a possibility.

Literature used for calculations

The article that is used as the basis for the calculations in this study dates from 2000. Data from this study is crucial for the outcome of this research. Therefore, it is important to mention that in the 17 years since publication the described technology can have changed. In the case the technology has improved, the theoretical yield and sustainability score of anaerobic digestion on neighbourhood scale can turn out higher.

Next to that, most of the calculations are based on figures of a full scale plant in Lelystad (Ten Brummeler, 2000). The data for the full scale plant were assumed to be applicable on a small scale plant as well. This assumption can have some limitations. For example, this research calculated that a 80,6 m3 reactor should be sufficient for the Wildemanbuurt. The size of a reactor can be crucial in urban areas with limited space. To what extent the projected size can differ from the actual required size is unclear. When the required size is much larger than calculated, it can make the realisation more difficult. Further research on how the use of the Biocel technology differs over scale is required to overcome this limitation.

Sustainability assessment

Sustainability can be explained in different ways and applied to different technologies, systems or concepts. Therefore, it is difficult to give an objective definition of sustainability. Sustainability is strongly dependent on case and scale specific circumstances (Southerton, Chappells, & Van Vliet, 2004). In this research the focus was on sustainability related to closing energy and waste cycles. Thereby the influence of anaerobic digestion on other cycles (e.g. water or air), was ignored. If the formulation of the definition of sustainability and the formulation of criteria was done with a different perspective, the outcome of this research could have been different. Therefore, it is important to mention that when communicating the results of this study, sustainability was assessed considering energy and waste cycles.

For the assessment of the sustainability, anaerobic digestion was considered as a carbon neutral way of energy production because the CO_2 emitted by burning the biogas is equal to the CO_2 uptake during biomass growth. However, as stated by Gerin, Vliegen, & Jossart (2008), also the emission caused by agricultural activities to grow biomass and emission caused by construction and operating the anaerobic digestion plant should be taken into account for a more complete sustainability assessment.

Assumptions on scale differences

In this research it is assumed that, more technological and financial resources are available on a larger scale. Following on this, the lack of knowledge and skills for complex system operation in the Wildemanbuurt is another assumption. This assumption was part of the motivation to select a rather simple anaerobic digestion system as the type of anaerobic digester most appropriate for the Wildemanbuurt. In reality this assumption can turn out to be false. The Wildemanbuurt is able to operate a more advanced system with a higher yield when the neighbourhood finds a party willing to invest in technology, skills or education. In that case the sustainability scores for neighbourhood scale anaerobic digestion can be higher, using the MCA described in this research.

Recommendations for further research

The Wildemanbuurt

This study was an explorative technical feasibility study. Meaning, before implementation of the project it is important to deeper investigate the possibilities for anaerobic digestion in the Wildemanbuurt. Neighbourhood specific waste data has to be collected in order to design a digester suitable for exact composition of the organic waste flow.

Next to that, a site specific technology comparison study, similar to Murphy & McKeogh (2004), can be done in order to determine the most appropriate waste treatment technology for the Wildemanbuurt.

Considering the long term, research commissioned by a forum on green gas in The Netherlands showed that in the future especially cow manure, seaweed, food processing waste and wastewater sludge have a high anaerobic digestion potential (RVO, 2014). These inputs are not, or to a limited extent available on neighbourhood scale. The organic waste flow in the Wildemanbuurt, as described in this research, exists for the major part out of fruit and vegetable waste. However, on city scale these inputs could be available. This could raise the question, when building an anaerobic digester, whether it is wisely to design it to run mainly on fruit and vegetable waste. Therefore, further research should also investigate the possibilities for co-digestion on city scale of organic waste with other inputs.

Digestate

This research states that anaerobic digestion of almost 400 ton of organic waste in the Wildemanbuurt produces almost 200 tons of compost. This research did not take into consideration the risks of using this compost as fertiliser. Also, the influence of harmful substances in the organic waste flow on the possibility to use the compost as a fertiliser are neglected. Further research is needed to investigate the full potential of reusing the nutrients in the compost produced by anaerobic digestion of organic waste in the Wildemanbuurt.

Sustainability assessment

As mentioned throughout this study, during further research it can be valuable to bring together relevant stakeholders and experts to formulate criteria and assign weights and scores. By doing this, the weights and scores can become a better representation of the (local) preferences.

Scale comparison

This research compares anaerobic digestion on neighbourhood scale with anaerobic digestion on city scale. One of these two scales is not necessary the 'best' scale to operate on. For further research it can be interesting to also investigate other scales, such as household or apartment complex. Next to that it can be interesting to explore options for scale combination. For example, decentralised anaerobic digestion and biogas production combined with centralised combined heat and power plants.

Infrastructure

The infrastructure for waste collection partly determines the possibilities for treatment. Waste collection infrastructure can be considered the first treatment step (Cecchi et al., 2011). The waste collection infrastructure was considered out of the scope of this research, however, it can be crucial for the success of anaerobic digestion of organic waste. Therefore, further research should investigate the possible organic waste collection infrastructures in the Wildemanbuurt and the consequences of these infrastructures for anaerobic digestion.

9. CONCLUSION

This research explored the possibility for anaerobic digestion in Amsterdam. It focussed on two scales, neighbourhood and city scale. A dry one-phase batch process under mesophilic is considered most appropriate for the Wildemanbuurt. The Biocel anaerobic digestion technology is used as basis for theoretical yield calculations. Out of the 399,8 ton organic waste produced per year, the Wildemanbuurt can produce 28 ton of biogas and 199,9 ton of compost per year.

A multi-criteria analysis is used to assess the sustainability of anaerobic digestion of organic waste on city scale and for the Wildemanbuurt. Environmental aspects, economic aspects and operational aspects were the criteria used for the analysis. A total of eight indicators are used to score the criteria. Five sets of weights are used; normalised weights (criteria are equally important), weights with an emphasis on environmental aspects, weights with an emphasis on economic aspects, weights with an emphasis on operational aspects and weights assigned by the author. For all the sets of weights, anaerobic digestion on city scale scores higher on the multi-criteria analysis. For all the sets of weights, the city scale scored higher than the Wildemanbuurt on environmental and operational aspects, the Wildemanbuurt scored higher on the economic aspects. Especially on operational aspects the city scale scores high compared to the Wildemanbuurt.

Anaerobic digestion on neighbourhood scale and on city scale both contribute to a more sustainable Amsterdam. Possibility and willingness to invest in technology and the availability of skills and knowledge are scale and case specific aspects that determine to what extent anaerobic digestion contributes to a more sustainable Amsterdam.

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Annex 1

List of interviewed companies

Name of the company	Type of company
Viswinkel Saïda	Fish shop
Baris	Shop; supermarket
Bon Apetit	Bakery
Lunchroom Soussi	Restaurant
Volendammer Vishandel C. Schilder	Fish shop
Shiv Roti	Restaurant
Kara Firin	Bakery
Ata Can	Shop; supermarket
Bessaha	Shop; supermarket and butcher
Cesme lunchroom	Restaurant
Cesme bakery	Bakery
Little Dragon	Restaurant
Snackbar Van Vliet	Snackbar
Turkse Shoarma	Restaurant
Banketbakkerij-Chocolaterie G. Roetman	Bakery
Slagerij Denkers	Shop; butcher
Bakkerij Imming	Bakery

Annex 2

Interview format

Naam bedrijf:					
Type bedrijf:	[ ] Restaurant [ ] Snackbar [ ] Shop; namelijk:				
Afval	**Soort**	**Hoeveelheid**	**Eigenschappen (nat/ droog etc)**	**Huidige infrastructuur**	**Kosten**

Annex 3

Data collected by interviews

Name:	Viswinkel Saïdia
Type:	Shop; viswinkel

Waste type	Amount (avg)	Unit	Characteristics	Current infrastructure	Others
Fish waste	70	kg/week	Wet offal.	Collected separately and is picked up.	
Oil	110	l/week		Collected separately and is picked up.	Financial compensation

Name:	Baris
Type:	Shop; supermarket

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Fruit and vegetables	12	kg/week		Not collected separately.	Reason for not separating waste is a lack of time. Owner is willing to separate the waste.

Name:	Bon Apetit
Type:	Shop; Bakery

Waste type	Amount (avg)	Unit	Characteristics	Current infrastructure	Others
Bread	17,5	kg/week	Dry	Is picked up and goes to a nearby farm.	

Name:	Lunchroom Soussi
Type:	Restaurant

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Swill	30	kg/week	Mix of all fruits, vegetables and food waste.	Collected separately and is picked up.	
Bread	6	kg/week	Dry.	Is picked up and goes to a nearby farm.	
Oil	8	L/week		Collected separately and is picked up.	Financial compensation
Others	20	kg/week	Mix of all other wastes.		

Name:	Volendammer Vishandel C. Schilder
Type:	Shop; viswinkel

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Fish waste	60	kg/week	Wet offal.	Collected separately and is picked up.	
Oil	120	l/week		Collected separately and is picked up.	Financial compensation (50eu).

Name:	Shiv Roti
Type:	Restaurant

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Others	30	kg/week	Mix of all wastes.	Is picked up.	Considers its wasteflows to small to start separating or participate in energy-project.

Name:	Kara Firin
Type:	Shop; Bakery

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Bread	15	kg/week	Dry	Is picked up and goes to a nearby farm.	

Name:	Ata Can
Type:	Shop; supermarket

Waste type	**Amount** (avg)	**Unit**	**Characteristics**	**Current infrastructure**	**Others**
Fruit and vegetables	12,5	kg/week		Collected separately and is picked up.	

Name:	Bessaha
Type:	Shop; supermarket and butcher

Waste type	**Amount** (avg)	**Unit**	**Characteristics**	**Current infrastructure**	**Others**
Fruit and vegetables	55	kg/week			
Offal	55	kg/week	Mix of bones, fat and other butchers' waste.	Is collected separately and is picked up once a week.	Costs are 26eu per pick up and there are strict laws on how to deal with waste for a butcher.

Name:	Cesme lunchroom and bakery
Type:	Restaurant

Waste type	**Amount** (avg)	**Unit**	**Characteristics**	**Current infrastructure**	**Others**
Bread	10	kg/week	Bread and other bakingwastes (dough etc).	Collected separately and is picked up or brought to the bread digester.	
Swill	45	kg/week	Mix of all fruits, vegetables and food waste.		
Oil	1	l/week		Collected separately.	

Name:	Little Dragon
Type:	Restaurant

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Others	60	kg/week	Mix of all wastes.	Is picked up.	

Name:	Snackbar van Vliet
Type:	Shop; snackbar

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Swill	15	kg/week	Mix of all fruits, vegetables and food waste.	Is picked up.	
Oil	3	l/week		Collected separately and picked up.	
Others	105	kg/week	Mix of all wastes.	Is picked up.	

Name:	Turkse Shoarma
Type:	Restaurant

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Others	30	kg/week	Mix of all wastes.	Transported to waste container by the owner.	

Name:	Banketbakkerij-Chocolaterie G. Roetman
Type:	Shop; bakery

Waste type	Amount	Unit	Characteristics	Current infrastructure	Others
Others	45	kg/week	Mix of all wastes.	Is picked up.	
Expired cakes	15	kg/week	Cakes and pies unable to be sold. Considered as unusefull for anaerobic digestion.	Not separated from normal waste.	

Name:	Slagerij Denkers
Type:	Shop; butcher

Waste type	**Amount**	**Unit**	**Characteristics**	**Current infrastructure**	**Others**
Others	30	kg/week	Mix of all wastes.		No seperate collection of vegetable or meat waste

Name:	Bakkerij Imming
Type:	Shop; Bakery

Waste type	**Amount**	**Unit**	**Characteristics**	**Current infrastructure**	**Others**
Bread	60	kg/week	Dry	Is picked up and goes to a nearby farm.	
Others	30	kg/week	Mix of all wastes.		

Restaurants	Swill	Frying oil	Bread	Fruits and vegetables	Offal	Others
Lunchroom Soussi	30	8	6	0	0	0
Shiv Roti	0	0	0	0	0	30
Cesme lunchroom *	45	1		0	0	0
Little Dragon	0	0	0	0	0	60
Turkse Shoarma	0	0	0	0	0	30
Total	**75**	**9**	**6**	**0**	**0**	**120**

Snackbars & fish shops	Swill	Frying oil	Bread	Fruits and vegetables	Offal	Others
Viswinkel Saïdia	0	110	0	0	70	0
Volendammer Vishandel C. Schilder	0	120	0	0	60	0
Snackbar van Vliet	15	3	0	0	0	105
Total	**15**	**233**	**0**	**0**	**130**	**105**

Bakeries	Swill	Frying oil	Bread	Fruits and vegetables	Offal	Others
Bon Apetit	0	0	17,5	0	0	0
Kara Firin	0	0	15	0	0	0
Cesme bakery *	0	0	10	0	0	0
Banketbakkerij-Chocolaterie G. Roetman	0	0	0	0	0	60
Bakkerij Imming	0	0	60	0	0	30
Total	**0**	**0**	**102,5**	**0**	**0**	**90**

Annex 4

Potential biogas yields based on data described by Braun (2007).

Potential biogas yields based on data described by Braun (2007).

	Amount	%H2O	%VSofTS	VS content input	biogas yield Typical	Biogasm3/week
	kg/week	Typical	typical	kg/week	m3/kgVS	
Swill	90	80	85	15	0,7	10,7
Frying oil	195	0	95	185	1,1	203,8
Bread	400	10	95	342	0,7	239,4
Fruits and vegetables	6030	80	80	965	0,4	385,9
Food	925	50	80	370	0,7	259,0
Organic residues	50	20	80	32	0,5	15,7

Total per week	1114,5	m3 biogas
Total per year	57953	m3 biogas