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Masterthesis

Design and implementation of a hybrid biogas plant to reduce environmental pollution and food waste

PROMOTOR :
Prof. dr. ir. Wim DEFERME

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dr. Michael J. SAULO

Tobias Corthouts, Daan Vanhoudt
Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: energie, afstudeerrichting elektrotechniek

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Preface

During our third year of engineering technology, we first heard about the possibility of doing our master's thesis in Kenya during a class given by Prof. Dr. Ir. Wim Deferme. We were immediately excited and a meeting followed later that year with more clarification about the project. We were going to implement a biogas installation in the Technical University of Mombasa. We were completely convinced and did not need much time to make the decision. During the first semester, we worked out the installation theoretically after which in semester two the real work could begin. For us, the implementation of our work added great value to this master's thesis. In this way, we learned to work with the few available resources, lead the project in the right direction and made adjustments where necessary. Besides the technical aspects, we were also confronted with the cultural differences of Kenya. But especially the hospitality, helpfulness and beautiful nature that the people and the country have to offer will stay with us. This project has made us evolve not only on a technical level but also as human beings. The experiences we have gained will definitely be useful for our future careers. Therefore, we would like to thank some people for their contribution that made all this possible.

First of all, we would like to thank Prof. Dr. Ir. Wim Deferme who assisted us in our work from the very beginning and made this international experience in Kenya possible for us. We could always turn to him with all our questions and his understanding and knowledge lifted this project to a higher level.

In addition, we thank our external supervisor, Dr. Michael J. Saulo. He was enthusiastic about the project from the beginning and we are grateful to him for making this possible. We received the best technical and organizational support, but he also took care of us from the first day in Mombasa. He was always there for us and ready to support us when needed.

This master's thesis is part of a development project of the non-profit organization Students for Energy in Africa. We would also like to thank the members of this organization for making this project possible.

We also thank everyone who has supported the project financially by making a donation or during our waffle sale. These additional funds have provided more opportunities that have taken the project to a higher level.

Last but not least, we want to thank our family, friends, and partner for the support and trust we received. We enjoyed sharing our experiences with you and in difficult moments we could always rely on you.

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Abstract

The Technical University of Mombasa provides hot meals for about 2,000 students a day. To achieve this, 800 kg of wood and 120 kg of LPG a month are needed. This master's thesis focuses on two major problems: the use of fossil fuels which contributes to global warming and the management of organic food waste. To address these issues, this master's thesis covers the design and implementation of a biogas installation. The installation processes organic waste from the kitchen in the most optimal way. This will produce biogas that will be used for cooking and digestate that will serve as a fertilizer.

A literature study was conducted to arrive at the optimal fixed-dome digester. The digester combined with a floating-drum gasholder was the first version of the system. At a further stage, this installation was expanded into a hybrid system. This was done by covering the overflow tank, which eliminates the gas losses in the tank and reduces greenhouse gases. In addition, the installation was expanded with a balloon-type digester, which provides better efficiency and a more complete digestion process. To determine the volume of the gasholder, a simulation was performed.

The hybrid biogas installation is expected to produce 11.88 m^3 of biogas a day, which reduces the energy consumption for cooking activities by 27%. Additionally, the system is also used as a pilot plant for educational purposes. As a further development of this project, the biogas production will be measured and the quality of the biogas and digestate will be analyzed.

Abstract (Dutch)

De Technical University of Mombasa voorziet warme maaltijden aan ongeveer 2 000 studenten per dag. Hiervoor is 800 kg hout en 120 kg LPG per maand nodig. Deze masterproef richt zich op twee grote problemen: het gebruik van fossiele brandstoffen, die bijdragen aan de opwarming van de aarde en het beheer van organisch voedselafval. Om deze problemen aan te pakken, behandelt deze masterproef het ontwerp en de implementatie van een biogasinstallatie. De installatie verwerkt organisch afval uit de keuken zo efficiënt mogelijk. Hierbij wordt biogas geproduceerd dat gebruikt wordt om te koken.

Er is een studie uitgevoerd om te komen tot de optimale fixed-dome vergister. De vergister in combinatie met een floating-drum gashouder was een eerste versie. In een volgend stadium werd deze installatie uitgebreid tot een hybride systeem. Dit is gedaan door de overflow tank af te dekken. Hierdoor worden de gasverliezen in de tank geëlimineerd. Daarnaast wordt de installatie uitgebreid met een ballontype vergister. Dit zal zorgen voor een betere efficiëntie en een vollediger vergistingsproces. Er is een simulatie uitgevoerd om het volume van de gashouder te bepalen.

De hybride biogasinstallatie produceert 11,88 m³ biogas per dag. Het energieverbruik voor kookactiviteiten kan met 27% worden verminderd. Bovendien wordt het systeem ook gebruikt als proefinstallatie voor educatieve doeleinden. Als verder verloop van dit project zal de biogas productie gemeten en de kwaliteit van het biogas en digestaat geanalyseerd worden.

1 Introduction

1.1 Situation

This project is part of a two-year project of the non-profit organization 'Students for Energy in Africa' (S.E.A.) [1]. S.E.A. realizes sustainable energy projects in Africa, researched and executed by students of Flemish colleges and universities in cooperation with the local community. The students go on-site to realize the project together with the local population. The realization of this project is done at the Technical University of Mombasa (TUM) [2]. Following Nairobi, Mombasa is the second-largest city in Kenya and it is located in the south-east of the country, along the Indian Ocean. In the past, S.E.A. has carried out a similar project in Senegal [3]. In this project, this previously acquired knowledge will be optimally used in combination with the experiences of similar projects and the knowledge of local companies and universities.

Most schools and universities in Kenya use energy sources such as liquefied petroleum gas (LPG), wood and other fossil fuels in their kitchens. The Technical University of Mombasa provides hot meals for about 2,000 students per day. To achieve this, 800 kg of wood and 120 kg of LPG per month are needed to sustain the cooking and heating activities of its main kitchen. The wood is mainly used in the scullery (Figure 1-1) where water is boiled for rice and beans, among other foods. In the main kitchen, the rest of the meals are prepared with LPG (Figure 1-2).

Providing hot meals every day in universities but also in smaller secondary schools results in large amounts of food waste. For the University of Mombasa, this amounts to about 100 kg per day [4]. Local markets are often left with a large amount of organic waste while these food residues could be used as an energy source.

Figure 1-1: Scullery of the university

Figure 1-2: main kitchen of the university

1.2 Problem definition

This project focuses on two major problems in the Mombasa region and by extension in Kenya. The first problem is the use of fossil fuels, such as wood and LPG that serve as fuel for preparing hot meals. In the kitchen of TUM wood fuel consisting of 45 kg charcoal and 110 kg firewood is used every day. These energy sources are quite expensive to purchase and contribute to greenhouse gas emissions and climate change. Wood fuel impacts the environment and the users negatively [5]. The kitchen staff, who spend a lot of time in the kitchen, experience the greatest impact. In Kenya, about 704,000 hectares are classified as primary forest, the most bio-diverse form of forest. However, Kenya loses an average of 12,600 hectares of forest per year due to the burning of firewood for charcoal. This amounts to an average annual deforestation rate of 0.34% [4]. The second development problem that this project attempts to address is the management of organic (food) waste. According to The Department of Environment, Waste Management and Energy [6], about 1,000 tons of solid waste is produced every day in Mombasa County.

1.3 Objectives

This master's thesis focuses on designing a biogas installation that converts food waste into biogas. The food waste from TUM will be used as biomass and the obtained biogas will be used for cooking in the kitchen of the university. The objective is to use the available food waste as efficiently as possible, to generate biogas and to replace wood fuel to the greatest possible extent. This wood fuel is used in the scullery and thus the biogas will be used here as well. This is used to cook the beans, rice and other types of food with in total 672 l of water a day. In addition to the biogas installation, a second project, carried out by Kjel Van Schijndel and Leon Vandenberghe, will implement a solar heater that will preheat water. This water will be used to cook the previously mentioned food in the scullery. The installation must be realized with locally available materials so that local communities can also realize similar projects. The project will be carried out in cooperation with the local population, contractors and entrepreneurs.

The most important requirement for this project is to make optimal use of the available organic waste. This will be done by creating an innovative biogas installation that steps away from the standard available designs, in order to achieve a higher gas production with the same feedstock. Most standard designs have no recent innovations. So another advantage from stepping away from the standard available designs, is that an innovation will be accomplished in biogas technologies. This means that the biomass (= 100 kg of food waste from the kitchen [4]) has to be converted into biogas as efficiently as possible, taking into account the available budget. As a benchmark, the performance of one of the most recent and only innovations in biogas technology in Kenia, the flexi biogas digester will be used. This digester is a patented technology from the company 'Flexi biogas solutions' [7], with an estimated gas production of 8.3 m^3/day per 100 kg of food waste [8]. In other words, the goal is to achieve a gas production that is higher than 8.3 m^3/day per 100 kg of food waste. The biogas installation is planned to be finished and running by the 16th of May 2021.

1.4 Method

As a first step, an extensive literature study will take place on the anaerobic digestion process that happens in the biogas installation as well as on the different types of biogas installations and the advantages and disadvantages of each type. The aim of this is to acquire sufficient knowledge about the possibilities. In the first semester, the type of standard biogas installation that will be used, has to be decided and has to be worked out conceptually. This concept will be presented to the project manager in Mombasa. To further develop and design the concept, sufficient knowledge about the energy consumption is needed. To get an overview of this, data will be collected in TUM's kitchen over several days. With this data, not only the quantity of the energy consumption must be established, but also the energy consumption pattern over time. Communication with the local person in charge in Mombasa is therefore necessary to obtain sufficient information.

The practical implementation of the project will begin on-site in Mombasa after finetuning the design. When arriving in Mombasa the theoretical design is mostly finished, based on the information obtained from the staff and students of TUM. On-site, the reliability of the information will be checked and the design will be further optimized. An innovative biogas installation (to maximize the gas production) will be developed by modifying the designed standard system. In order to obtain additional information and knowledge for this modification, local universities with specialized biogas departments and companies that deal with biogas installations will be visited. The final design of the modified system will be established in consultation with the promoters and other stakeholders.

Once the final design is established, practical work can begin. The tasks performed on site in Mombasa, correspond to the tasks of a project engineer. These tasks include contacting companies, making the necessary calculations and drawings as well as planning, assisting and monitoring the construction. When the biogas installation is finished, assistance will be given for the start-up of the biogas installation. In the final phase, the installation will be extensively tested, the appropriate people will be trained to further maintain the installation and data will be collected and analyzed.

2 Anaerobic digestion - process

Anaerobic digestion (AD) is a microbiological process in which organic material is broken down. It is the biochemical decomposition of organic material by various micro-organisms in the absence of oxygen. By studying the process, a better understanding of the anaerobic digestion process is obtained. In this way, this process can be applied as efficiently as possible to convert organic biodegradable material into biogas. Besides energy-rich biogas, this decomposition process produces a nutritious digestate that can be used as a fertilizer.

This form of renewable energy not only reduces the use of fossil fuels and the associated greenhouse gases, it also reduces the large quantities of organic waste.

As mentioned above, anaerobic digestion takes place in the absence of oxygen, as opposed to aerobic digestion. Aerobic bacteria have shorter reproductive cycles in contrast to anaerobic bacteria, which means that the degradation process takes place more quickly in the presence of oxygen. Aerobic micro-organisms ensure a more efficient degradation but consume more energy themselves, while anaerobic micro-organisms leave some of this energy unused. This energy is then released in the form of biogas.

The amount of energy or calorific value of the biogas depends on the methane content. Biogas consists on average of 55-70 Vol.-% methane which brings the calorific value of biogas to around 6.0-6.5 kWh/m³. Table 2-1 compares the calorific value of different fuel sources with that of biogas [9].

Table 2-1: Calorific value for different fuel sources [9]

Fuel Source	Calorific Value	Equivalent to 1 m³ Biogas (approx. 6.0-6.5 kWh/m³)
Biogas	6–6.5 kWh/m³	
Diesel, Kerosine	12 kWh/kg	0.50 kg
Wood	4.5 kWh/kg	1.30 kg
Cow dung	5 kWh/kg dry matter	1.20 kg
Plant residues	4.5 kWh/kg dry matter	1.30 kg
Hard coal	8.5 kWh/kg	0.70 kg
Propane	25 kWh/m³	0.24 m³
Natural gas	10.6 kWh/m³	0.60 m³
Liquefied petroleum gas	26.1 kWh/m³	0.20 m³

2.1 Feed material and biogas yield

Biomass that serves as feed for the digester consists of water and dry solid matter (Total solids (TS)). Of this dry matter, only the organically decomposable part (or volatile solids (VS)) contributes to biogas production. The organic dry solid content (ODS) can vary from 70% to over 95%. Biomass with an ODS of less than 60% is not considered valuable. Table 2-2 gives the (organic) dry matter content for various feed materials [9].

Table 2-2: Total Solids (TS) and Volatile Solids (VS) *for different feedstocks [9]*

Substrate	TS (%)	VS (%)
spent fruits	25 –45	90 –95
Vegetable wastes	5 –20	76 –90
Market wastes	8 –20	75 –90
Leftovers (canteen)	9 –37	75 –98
Overstored food	14 –18	81 –97
Fruit wastes	15 –20	75 –85
Biowaste	25 –40	50 –70
Kitchen waste	9 –37	50 –70
Market waste	28 –45	50 –80

Thus, the biogas yield depends on the organic dry matter content of the biomass, but also on other factors such as temperature and mixing. Therefore, the so-called biological methane potential (BMP) is also used. This indicates the maximum amount of methane gas that can be produced from a certain amount of solid organic waste. Table 2-3 gives the methane yields for different types of feed material [9].

Table 2-3: Biogas yield of anaerobic digestion of organic solid waste [9]

Substrate	Methane Yield (L / kg VS)
Palm oil mill waste	610
Municipal solid waste	360–530
Fruit and vegetable wastes	420
Food waste	396
Rice straw	350
Household waste	350
Swine manure	337
Maize silage and straw	312
Food waste leachate	294
Lignin-rich organic waste	200

Feeding the plant with feed material can be done in either continuous or batch mode. In continuous mode, biomass is added incrementally at intervals while the same amount of digestate leaves the digester. This creates a continuous anaerobic digestion process. When feeding the digester is done batch by batch, a quantity of biomass is fed to the digester after which it is sealed airtight. After a certain retention time, the digester is opened and emptied. For each batch, the start-up phase takes place again so that the gas yield is not stable. The airtight sealing of the digester is an additional difficulty.

2.2 Digestion process

The organic matter that is part of the feed material is converted by various microorganisms into biogas on the one hand and a mixture of bacterial biomass and inert organic matter on the other. The latter is also called digestate or effluent. The following phases can be distinguished in the digestion process: hydrolysis, acidification, acetic-acid formation and methane formation.

Hydrolysis is usually the slowest of the four degradation steps. The acidogenic bacteria transform complex organic materials into liquid monomers and polymers. This conversion of higher mass organic molecules into soluble organics or simple molecules is very important because organic materials are simply too large to be directly absorbed and used by microorganisms as a food source. In the subsequent acid phase, these same bacteria convert the soluble organic material into volatile organic fatty acids and alcohols. The breakdown of amino acids also leads to the production of ammonia.

During acetic-acid formation, both the organic acids and alcohols are then transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. During this reaction, both BOD (biological oxygen demand), COD (chemical oxygen demand) and pH are lowered.

In the final stage, methane is formed. In this process, methanogenic bacteria convert hydrogen and acetic acid to methane gas and carbon dioxide. Methanogenesis is influenced by the conditions in the reactor such as temperature, feed composition and organic load. The gaseous product, biogas, consists mainly of methane (CH_4) and carbon dioxide (CO_2) but also contains several other gaseous "impurities" such as hydrogen sulfide, nitrogen, oxygen and hydrogen (Table 2-4). Biogas with a methane content of more than 45% is flammable; the higher the CH_4 content, the higher the energy value of the gas [9], [3], [10].

Table 2-4: Typical composition of biogas from bio-waste [9]

Components	**Symbol**	**Concentration**
Methane	CH_4	55 –70
Carbon dioxide	CO_2	35 –40
Water	H_2O	2 (20 °C) –7 (40 °C)
Hydrogen sulphide	H_2S	20 –20,000 ppm (2%)
Nitrogen	N_2	< 2
Oxygen	O_2	< 2
Hydrogen	H_2	< 1
Ammonia	NH_3	< 0.05

2.2.1 Influence of temperature on the digestion process

Anaerobic digestion is possible in just about all climatic conditions. However, at low temperatures (average temperature below 15°C) it is appropriate to use a heating element and insulate the digester. These additional costs can make the biogas system uneconomic. Not only the average temperature is an important factor to take into account, but also temperature fluctuations have a great influence on the digestion process. This can be avoided by digging the digester in and thus making use of the heat capacity of the earth.

The fermentation process has two ideal temperature ranges: one at 30-40 °C for mesophilic microorganisms (optimal temperature 37°C) and one at 45-60 °C for thermophilic microorganisms (optimal temperature 55°C). In the low-temperature range, the process is more stable because mesophilic microorganisms are more resistant to environmental influences. In addition, they also consume less energy but the reaction occurs more slowly and a longer retention time is required. If the digester operates in the high-temperature range, this leads to about 50% more degradation and therefore a higher biogas yield. This thermophilic operation, on the other hand, is less stable and requires more energy so thermophilic operation is chosen in developing countries [9].

3 Overview of biogas technologies

In this chapter, different technical characteristics of a biogas installation are discussed. The purpose is to create an overview of the different aspects of a biogas installation and to discuss different technologies. With this information, a concept can be developed for the biogas installation in TUM.

3.1 Comparison between low-tech digesters and industrial digesters

In the following section, low-tech digesters and industrial digesters are briefly and generally discussed and compared.

3.1.1 Low-tech biogas digesters

Most digesters in developing countries are low-tech/household digesters. Such digesters use locally available materials which reduces the cost of a biogas installation. However low-tech digesters require manual feeding of the biomass to the digester. They are not the most optimal solution in terms of gas production and efficiencies but the gas production and efficiency are certainly still sufficient. Low-tech digesters do not use pump systems and agitators, which simplifies the operation, lowers the cost and reduces electricity costs. The only equipment that requires electricity that may be needed in a low-tech digester is a shredder. An electric shredder can certainly be avoided in smaller domestic installations. Where the big advantage is that the biogas installation does not require electricity at all. The shredder is further discussed in section 7.1. Due to a large amount of food waste per day, an electric shredder is probably required for the installation in TUM.

3.1.2 Industrial biogas digesters

Industrial digesters are more specifically designed to the demands and needs of the system and client. Two examples of industrial installations are shown in Figure 3-1. This type of digester usually uses high-tech solutions and materials which naturally increases the cost of such an installation. Such installations often operate under optimum working conditions obtained through monitoring and heating of the digester, agitators and a more automated operation compared to a low-tech digester. The materials and components necessary to build an industrial plant may not be locally available, so import costs possibly increase the cost of the plant. Additional components such as electronics for monitoring and keeping the temperature constant, a pumping system with associated piping, agitators and covering/shielding of the installation increase the investment cost. Figure 3-1 shows an installation that uses a generator to generate electricity. In the situation of TUM, the gas produced will be used entirely for cooking. The generator would therefore increase investment costs and would not be profitable and unescissery for this project.

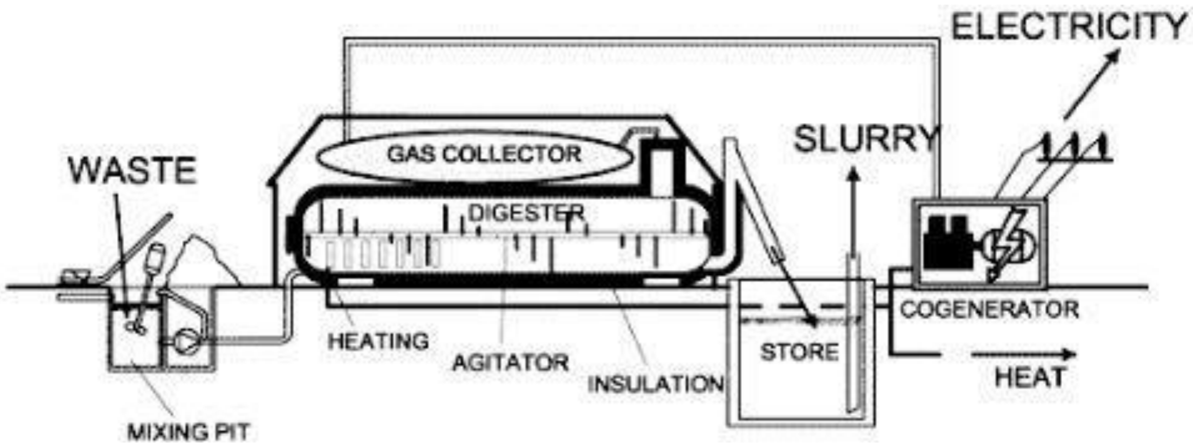

Figure 3-1: Steel vessel digester with separate balloon gasholder [11]

3.1.3 Conclusion and selection

In order to make a correct choice, not only the short-term objective must be taken into account, but also the long-term objective. These objectives are described in the project proposal as follows:

> By focusing in this project on the cooking and heating process at TUM's kitchen as a pilot system, we will investigate if the use of organic waste and renewable and sustainable energy can be applied for cooking purposes in local communities in the region of Mombasa and especially in secondary boarding schools which have high production of food waste due to the daily production in the boarding schools. It is our aim therefore, not only to construct this innovative cooking and heating process to solve a problem at TUM but also, and most importantly as a training tool for staff and students and for dissemination to local communities (with a focus on secondary boarding schools) [4, p. 3].

It is, therefore, necessary to take into account not only the situation of TUM but also the situation of local schools. In this way, this installation is more relevant for dissemination to local communities with fewer resources and more limited access to electricity.

The main difference between a low-tech installation and an industrial installation is that the investment cost and operation costs of a low-tech installation are lower while an industrial installation is more efficient. Most of the properties of an industrial installation are unnecessary and not essential for TUM. These unnecessary features are partially automated operation, agitators for higher efficiency and a more specialized design with possibly more expensive materials.

In local communities, in particular secondary boarding schools, an industrial installation is not at all necessary and probably not possible. This is because of the limited access to electricity, the cost of electricity and the limited knowledge to operate an industrial installation. An industrial plant would therefore make only a limited contribution to the long-term objectives of the project.

In order to get a higher efficiency without using high-tech components, a hybrid biogas installation can be designed. This hybrid plant will consist out of two low-tech technologies. By combining different low-tech technologies/installations, a bigger plant with higher overall efficiency can be obtained. If this option is chosen, a pilot plant will be built showing three possible technologies (the hybrid system and the two separate technologies). These low-tech technologies will be accessible for local schools and communities. Therefore, these biogas technologies can be disseminated to the local schools and communities. Because of this, the long-term objective will be maintained. The disadvantage of a hybrid system is the additional investment costs. However, a big advantage is that an innovation will be made in low-tech biogas digesters by obtaining a high efficiency using low-tech biogas technologies.

The low-tech digester in combination with a heat exchanger system (Optimized low-tech digester) can combine the advantages of both types of installations. By monitoring the temperature of the digester and keeping the digester at optimal temperature, the efficiency and gas production of the installation is increased. A heat exchanger can be integrated into the digester while the digester retains all its other properties related to a low-tech installation. The disadvantage of a heated digester is the additional investment costs and the additional electricity costs. The additional investment costs include piping, a pumping system and a heat source. Consideration can also be given to how the supply of food waste and water can be optimized with as little labor as possible while maintaining the low-tech design and with no or very limited additional investment costs. The properties of the three types of installations are summarized in Table 3-1.

Table 3-1: Discussion of the different types of installations

	Low-tech digester	**Hybrid low-tech digester**	**Optimized low-tech digester**	**Industrial digester**
Locally available materials	Yes	Yes	Yes	No
Electricity needed	Not at all	Not at all	Yes, but limited	Most electricity needed of the 3 types
Relevant for the long-term objective	Yes, relevant	Yes, relevant and shows 3 technologies for dissemination instead of 1	Less relevant	Limited relevance
Simplicity of the operation	Simple operation	Simple operation	Simple operation	More complicated operation, but partially automated
Feeding of the biomass	Manually	Manually	Manually, but as efficient as possible	Manually, but as efficient as possible or partially automated
Investment costs	Low	Mediocre	Mediocre	High
Operation costs	Low	Low	Mediocre	High
Gas production and efficiency	Mediocre	Higher gas production and high efficiency	Higher gas production and high efficiency due to optimum operating temperature	Most gas production and highest efficiency of the three types

For the following reasons, a hybrid low-tech digester is chosen. Table 3-1 shows that the hybrid low-tech digester achieves high efficiency with almost no compromises in comparison with the low-tech digester. The only disadvantage in comparison with the low-tech digester is the higher investment cost. The hybrid system is even more relevant for the long-term objective than the low-tech digester because it will show three technologies that are possible for dissemination instead of just one. The optimized low-tech digester and the industrial digester score more negative on most factors (see Table 3-1). Designing a hybrid biogas installation can create a new innovation in low-tech biogas installations.

A biogas digester is an old technology that has been well documented since the mid-nineteenth century [12]. Despite the age of (low-tech) biogas technologies, not many recent innovations have been made. Because of this, most low-tech digesters still have some flaws such as low efficiency, high gas losses and therefore higher emission of greenhouse gasses (such as carbon dioxide, methane and nitrous oxide [13]). It can be concluded that an innovation e.g. a hybrid installation is more than welcome in biogas technologies.

The hybrid plant will be developed as follows. First, a standard biogas installation will be conceptually designed and dimensioned. The standard installation is chosen so that it also has great potential as a stand-alone installation. In this way, it can serve as a stand-alone technology for the long-term objective of the project. After that, the shortcomings of this installation will be examined and existing low-tech technologies and their potential to solve these problems will be examined. Then the hybrid installation will be designed and dimensioned.

3.2 Types of biogas installations

In this section, the different types of biogas installations are reviewed in order to create an overview of the different possibilities. Based on this, a well-founded choice can be made for the basic biogas installation that is most suitable for this project. The choice of the basic design of the biogas installation is influenced by several factors: cost efficiency, the availability of local materials for the construction of the installation, the extent to which the temperature remains constant (without using an external heating element), the climate in which the biogas installation is located and the type of biomass.

The three most common biogas installations in developing countries are the fixed-dome digester, the floating-drum digester and the balloon-type digester. These digesters are wet[1] digestion systems that operate in continuous mode under mesophilic conditions. These three types of digesters have several important advantages for developing countries: they are cheap, can be built with locally available materials, are easy to use and have no or few moving parts, which limits wear and tear and guarantees a long lifespan. A fourth interesting type of biogas installation is the garage-type digester. The main difference with the previously mentioned biogas installations is that the garage-type digester is used as a dry digester in batch mode [9]. The last type of biogas installation that will be discussed is a hydraulic biogas installation.

Figure 3-2 provides a systematic overview of the four listed biogas installations that are suitable for use in developing countries. Each of these biogas installations is discussed further.

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[1] "Wet anaerobic digestion systems which use organic material with consistency of 10-20% dry matter or less and dry anaerobic digestion systems for organic matter with consistency of 20-40% dry matter or more" [63, p. 1].

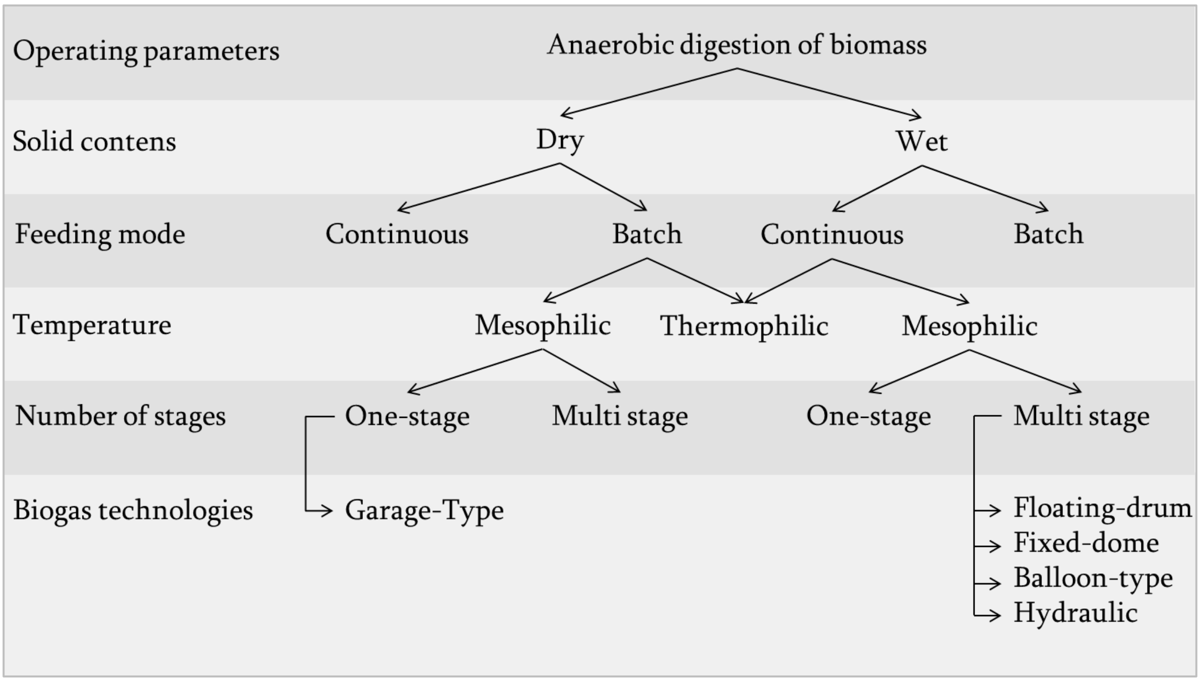

Figure 3-2: Types of biogas digesters eligible for developing countries [9]

3.2.1 Fixed-dome digester

The fixed-dome digester is a commonly used type of digester in developing countries. A fixed-dome biogas installation consists of a closed dome-shaped digester with a fixed gasholder, an inlet tank and an overflow tank. A schematic representation is shown in Figure 3-3. The biomass is fed into the digester through the inlet. The produced biogas accumulates in the upper part of the digester, the so-called storage section or the gasholder. When the gas outlet is closed, the gas pressure in the digester increases due to gas production, which pushes the digestate into the overflow tank. When the gas outlet is open, the gas pressure drops and a proportional amount of digestate flows back from the overflow tank into the digester. The gas pressure thus does not remain constant because it changes proportionally to the amount of gas stored and depends on the height difference between the two slurry levels (the slurry level inside the dome and inside the overflow tank). Usually, a fixed-dome digester is built underground, protecting the digester from low temperatures at night and from cold seasons. The surrounding soil compensates for the forces from the pressure build-up in the digester (0.1-0.15 bar at normal conditions). A fixed-dome digester can process animal manure along with fibrous substances because the daily movement of the substrate breaks down the scum layer. Generally, the plant operates in a continuous feeding mode, but if the overflow tank is large enough, biomass collected over several days can be fed to the plant [14].

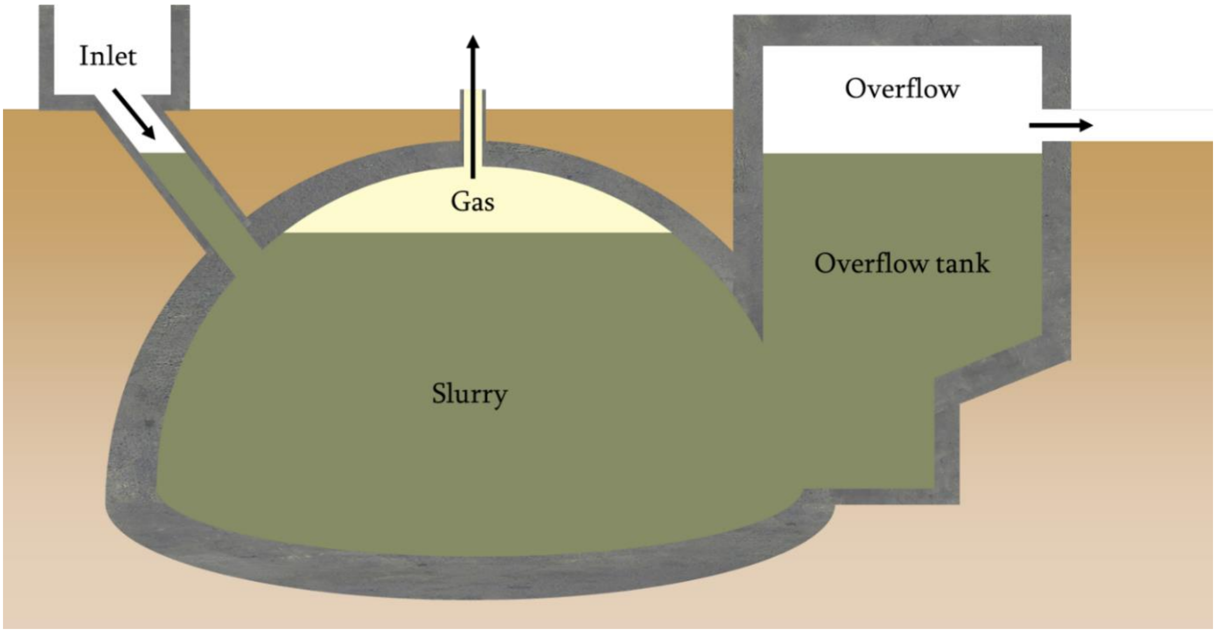

Figure 3-3: Schematic representation of a fixed-dome digester [9]

The construction of a fixed-dome digester is labor-intensive and requires expert supervision. It is important that the construction is airtight. In general, fixed-dome digesters are characterized by low initial costs and a long lifespan (about 15-25 years), as there are no moving and corroding parts involved. However, the masonry is susceptible to porosity and cracks, which normally prevent the masonry from being gas-tight. Porosity can be counteracted using special sealants such as paints with elastic properties in order to bridge the cracks, however, cracks often cause irreparable leaks. The fluctuating gas pressure in this type of digester can make the use of gas less ideal but generally doesn't form a problem [14].

3.2.2 Floating-drum digester

A floating-drum digester consists of a cylindrical digester and a movable, floating gasholder (gas drum). A schematic representation of a floating-drum digester is shown in Figure 3-4. This gas drum can rise or lower depending on gas production and gas consumption. The level of the drum thus gives a visual indication of the available quantity of gas. Through this rising and falling of the drum, the constant gas pressure in the digester can be guaranteed. This gas pressure can be regulated by attaching weights to the top of the drum [9].

The gas drum floats either directly on the biomass or in a separate water jacket, depending on the gas pressure in the digester or gas drum. This water jacket reduces methane leakage. A guiding frame inside the gas drum prevents the drum from tipping when it is raised (see "guide pole" in Figure 3-4). Floating-drum digesters that use a water jacket are usually easy to maintain [9].

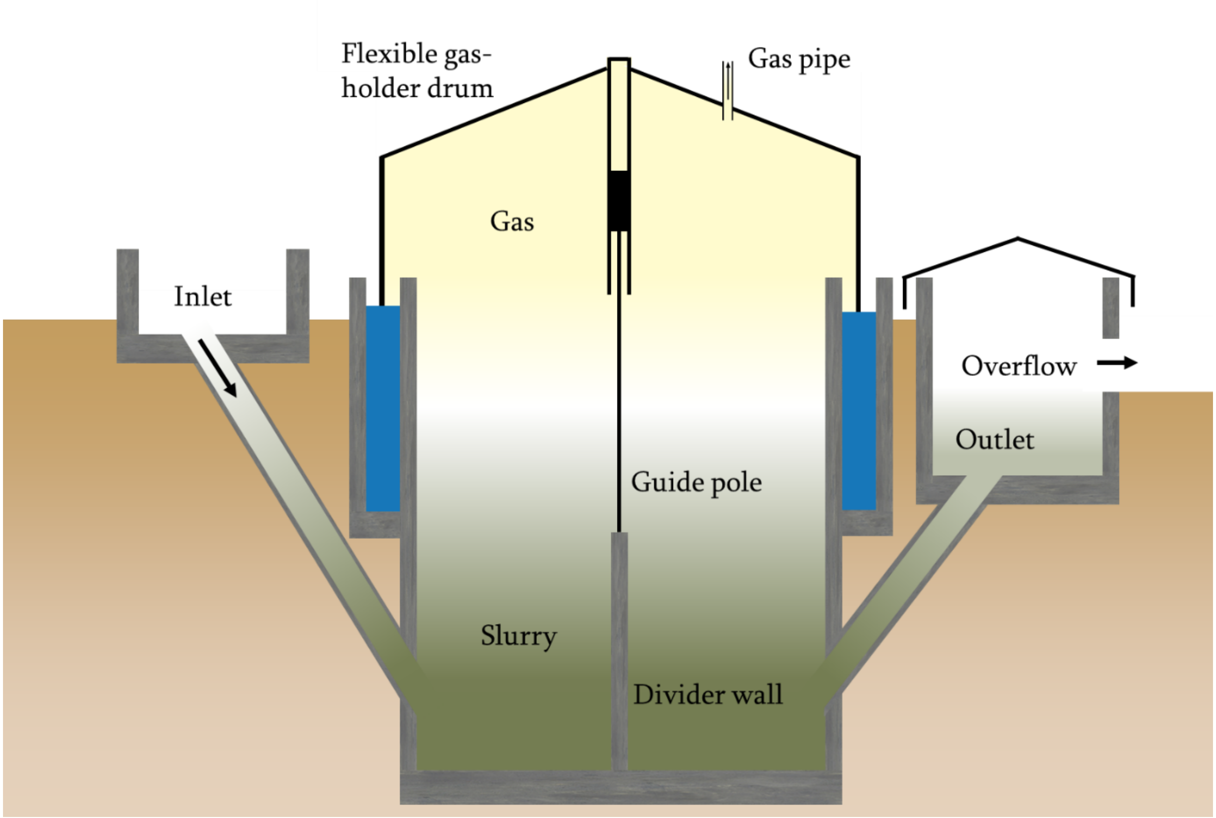

Figure 3-4: Schematic representation of a floating-drum digester [9]

The digester is usually made out of bricks, concrete, or masonry with plaster and the gas drum is usually made out of metal. The drum must be coated with waterproof paint to prevent corrosion. The right primer is crucial, so at least two primer coats and one top coat of plastic or bituminous paint must be applied. The top coats should be reapplied annually. The lifespan of a properly maintained gasholder is 3 to 5 years in a humid climate and 8 to 12 years in a dry climate. The lifespan of the digester itself is more than 15 years [14]. The digester is usually constructed underground while the metal gasholder is located above ground [9].

3.2.3 Balloon-type digester

A balloon-type digester consists of an elongated, heat and weather resistant plastic or rubber bag, which serves as both a digester and a gasholder. The gas is stored in the upper part of the balloon. The in- and outlet are directly connected to the balloon. A schematic representation of a balloon-type digester is shown in Figure 3-5. Due to the elongated shape of the digester, the biomass will never flow directly from the inlet to the outlet. The possibility of active mixing is limited and the slurry flows through the digester as a prop stream. The gas pressure can be increased by placing weights on the balloon. However, there needs to be paid attention to not damage the balloon [9].

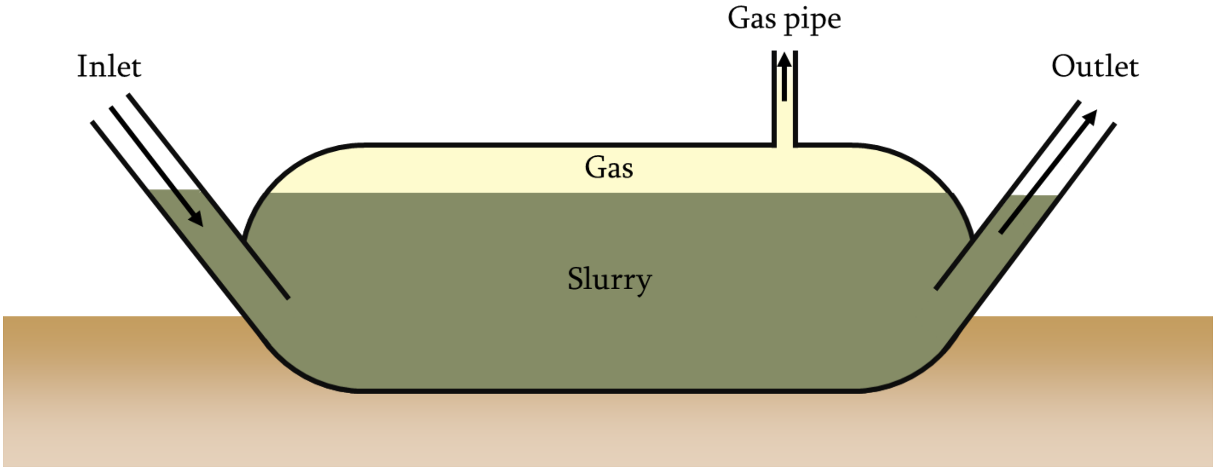

Figure 3-5: Schematic representation of a balloon-type digester [9]

The advantage of the balloon-type digester is that it can be built at a relatively low cost. The digester is placed above ground or slightly underground. This makes it suitable for areas with a lot of groundwater. However, the plastic/rubber balloon is rather fragile, it is sensitive to mechanical damage and it has a relatively short lifespan of 2 to 5 years, but there are systems (e.g.: flexi biogas [15]) with a longer lifespan of up to more than 15 years. But these newer systems have not been on the market long enough to verify the longer predicted lifespan. The digester is sensitive to temperature variations and extremely low or extremely high temperatures have a big negative effect on the digestion process. The digester, therefore, needs some form of protection and insulation against extreme weather, but this increases the cost of the installation. The balloon-type digester generally needs less biomass as feedstock than the fixed-dome and floating-drum digester to produce the same amount of gas. In addition, this type of digester provides sufficient flow of the biomass, resulting in more biogas production [14]. Another advantage of the balloon-type digester is that it is a horizontal digester. When new biomass is introduced, the existing biomass shifts to the outlet side, so the fresh biomass is not mixed with the already present biomass. This results in a higher biogas yield. One more advantage is that the digestion process, when the slurry leaves the digester, is almost 100% complete. This makes this type of digester very efficient. It ensures that the digestate is very watery and an excellent fertilizer without odor (as the N_2 is almost completely removed) [16].

3.2.4 Garage-type digester

Unlike the digesters discussed earlier, the garage-type digester is operated in batch mode and uses a dry digestion process. The garage-type digester is filled with biomass in batches and is closed with an air-tight door. During the digestion process, the biomass does not need to be transported or mixed. Because the installation is filled in batches, several digesters have to operate in parallel to obtain a continuous gas flow. A schematic representation of a garage-type digester is shown in Figure 3-6.

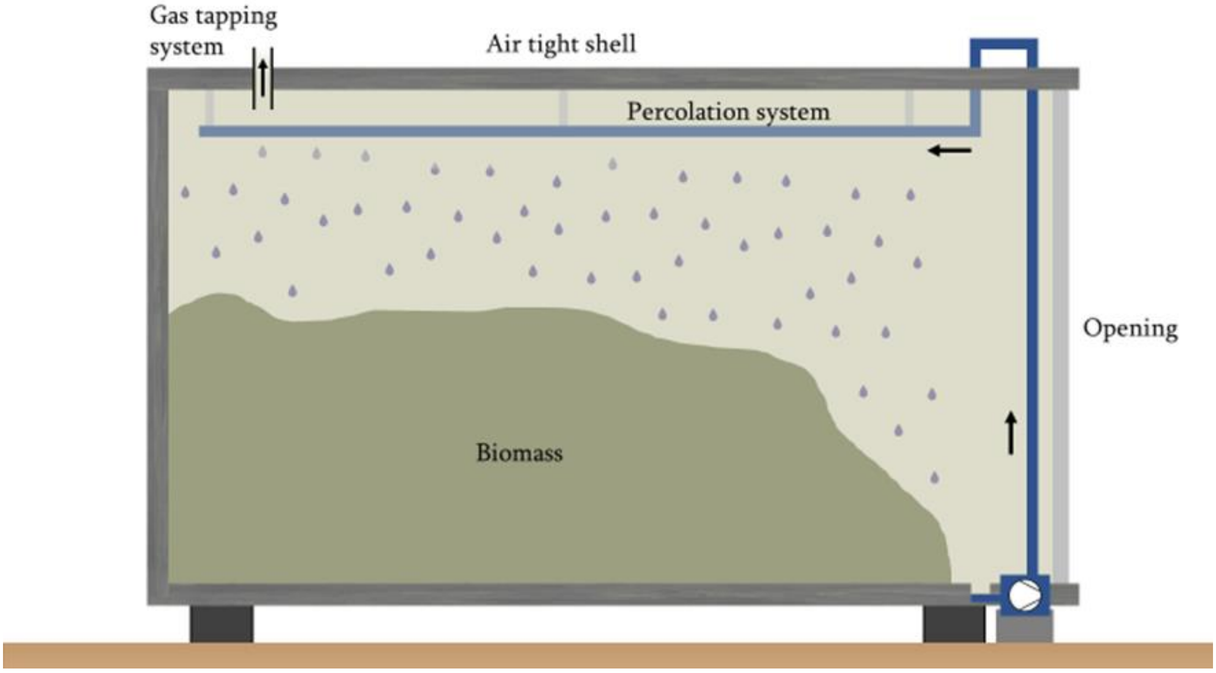

Figure 3-6: Schematic representation of a garage-type digester [9]

In a dry digestion process, water still plays a crucial role. The bacteria involved in the anaerobic digestion process need a wet environment because they are only active in the liquid phase of the substrate. The term "dry digestion" indicates a concentration of solids higher than 15%.

The fresh biomass is inoculated with old digestate or with fresh cow manure to initiate and speed up the digestion process. After closing the door of the installation, the percolation system (a spraying installation on the roof of the digester) is activated. The installation sprays percolate evenly over the biomass, spreading anaerobic bacteria. This percolate seeps through the biomass to the bottom of the installation, where the leachate is collected in an external storage tank via a filter. A pump system ensures recirculation of the percolate, in this way the biomass is regularly watered with percolate. Before the door of the digester is opened, the installation is flushed with exhaust gas (CO_2) from an engine to prevent the formation of an explosive gas/air mixture. Without flushing, this explosive mixture could occur when the digester is opened and during the emptying of the digester.

Despite the more complicated operation of the garage-type digester compared to the previously discussed digesters, experts claim that this type of digester has great potential in developing countries. The plant has a simple design, needs little water and simple and safe use of the digestate is possible [9].

3.2.5 Hydraulic biogas digester

The hydraulic digester is mainly used when the biomass consists of food waste and possibly sewage. This type of biogas installation is designed to combine the advantages of the fixed-dome and floating-drum digester and to solve the technical problems of these two digesters. The digester consists of a concrete belly, a concrete neck, a gasholder made of synthetic fiber material and a vertical inlet and outlet [17]. The vertical position of the inlet prevents the slurry from entering. An inclined outlet is often used so that the slurry can leave the digester more easily [18]. A schematic representation of the digester is shown in Figure 3-7

Figure 3-7: Schematic representation of a hydraulic biogas installation

Figure 3-8: PUXIN Hydraulic biogas system

and Figure 3-8: PUXIN Hydraulic biogas system Figure 3-8.

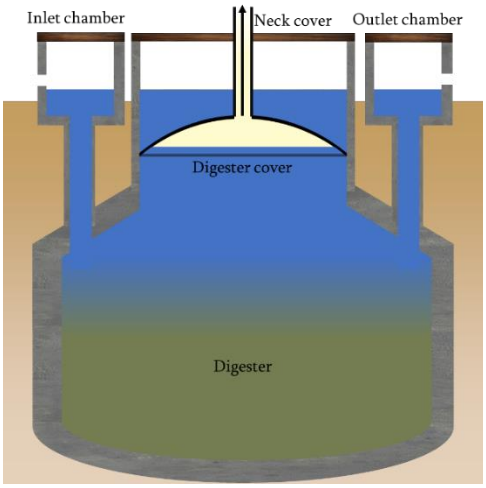

Figure 3-7: Schematic representation of a hydraulic biogas installation [17]

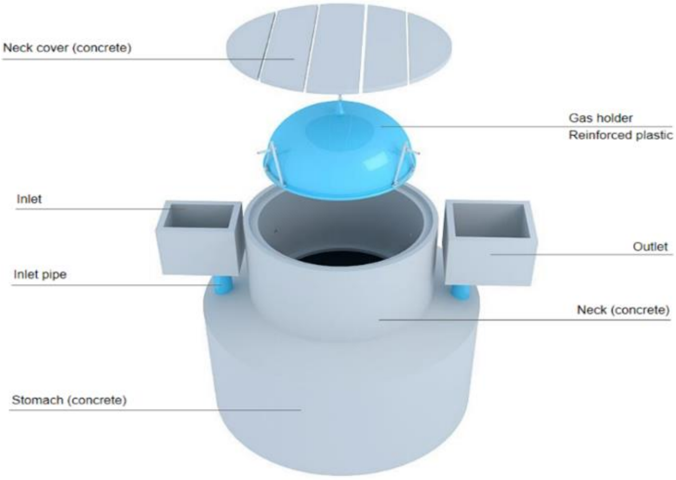

Figure 3-8: PUXIN Hydraulic biogas system [18]

The digester functions as a hydraulic system in which the entire digester is filled with water up to the same level, as can be seen in Figure 3-7

Figure 3-7: Schematic representation of a hydraulic biogas installation

Figure 3-8: PUXIN Hydraulic biogas system

. The decomposition of the biomass takes place underwater, therefore creating ideal anaerobic conditions that are crucial for the production of methane in the digester. The water also provides constant pressure. The biogas will be produced in the bottom of the digester and will rise to the top and is collected in the gasholder. When the volume of produced gas increases, the volume of gas will replace the volume of water and the water will move downwards. As a result, the water will exert upward pressure on the gas. The gas and the water thus perform equal but opposite reactions on each other. This ensures that the biogas in the gasholder always has constant pressure. This pressure can be as high as 8 kPa [17].

However, to enter the digester, the gasholder has to be removed first, which can be labor-intensive. In addition, reattaching the gasholder requires a trained technician [18]. The digester can be cleaned through the gasholder. As a result, any type of organic material can be used as biomass. This is not always the case with, for example, the fixed-dome digester (depending on whether the digester has a manhole or not), where it is not practical to empty the digester. Organic waste such as leaves, straw, grass, etc. does not decompose to the same extent as animal manure, leaving behind solid waste after decomposition. This solid waste must be removed from the digester before new biomass can be applied. As mentioned, the gasholder can be taken out of the digester so that the waste can be easily removed [14]. The disadvantage of this digester compared to the previously discussed types is that water storage pits must be provided.

The concrete construction ensures a long lifespan, comparable to that of the fixed-dome digester (15-20 years). But because the digester itself is cylindrical, a shorter lifespan can be expected than a dome-shaped fixed-dome digester [19]. The glass fiber reinforced plastic gasholder has a lifespan of about 10 years according to the Hydraulic Biogas System designed by PUXIN (Figure 3-8). When the gasholder is worn out, it can be replaced by a new one. However, the PUXIN digester has not been on the market long enough to guarantee the mentioned lifespan of the gasholder [18].

3.2.6 Summary and choice of biogas installation

The advantages and disadvantages of the discussed biogas installations are summarized in *Table 3-2*.

Table 3-2: Summary of the discussed biogas installations

	Construction cost	**Ease of construction**	**Durability**	**Locally available materials**	**Gas pressure**	**Maintenance**	**Other**
Fixed-dome	+ Low	+ Simple construction – Soil must be suitable for exploitation – Airtight construction requires expertise	+ No moving parts – Possibility of gas leakage if masonry is not good	+ Yes	– Depends on volume of stored gas	– Difficult to repair	+ Underground construction is space-efficient and limits temperature fluctuations
Floating-drum	– High material cost for steel drum	+ Relatively simple construction + Construction defects do not lead to major problems in operation and gas output	– Parts prone to corrosion	+ Yes	+ Constant	– Regular maintenance for the paint layer on the drum	+ Visual representation of volume of gas in storage – Gasholder can get stuck if it floats on the substrate in the digester
Ballon-type	+ Low	+ Easy to build + Not built deep underground, therefore suitable for areas with a high groundwater table	– Short lifespan – Prone to mechanical damage	– Material is often not available locally	– Low gas pressure requires additional weight on the balloon	+ Easy emptying and maintenance – Technician with expertise required for balloon repairs	+ Easy to transport + High digestion temperatures in a warm climate

	Construction cost	Ease of construction	Durability	Locally available materials	Gas pressure	Maintenance	Other
Garage-type	+ Low	− Door has to be airtight	+ Long lifespan	− No	− No	+ Easy to maintain as the digester can be easily accessed	+ Little water addition required − Each new batch must be injected with old digestate − Pump is required − No continuous gas supply with one installation − Flushing with CO_2 required before opening the door
Floating-drum	+ Low	− Soil must be suitable for exploitation − Waterproof construction required − Possibility of gas and water leakage if masonry is not good	+ No moving parts or Parts susceptible to corrosion − Relatively short lifetime of gasholder	− The plastic gasholder is usually not locally available	+ Constant	+ Gas or water leak is easy to see + Maintenance in the digester is safe because of large neck − Gasholder has to be removed for maintenance	− Water storage pits are required, which means that the system takes up more space

The fixed-dome, floating-drum and hydraulic digester are potential digesters for the project in TUM. They are simple in construction and have a long lifespan. The major disadvantage of the balloon-type digester is its sensitivity to mechanical damage. The major disadvantage of the garage-type digester is that it is a batch-type digester and that this digester has a more difficult operation compared to the other digesters. Of the three potential digesters, the fixed-dome digester is the only digester that cannot provide continuous pressure. However, this continuous pressure can be guaranteed if an external gasholder is used with a design that guarantees a continuous gas pressure. In chapter 5, the gasholders are discussed. An external gasholder that guarantees constant pressure has to be chosen, the motivation and more information about this can be found in chapter 5.

Because an external gasholder will be used that guarantees a constant pressure, the constant pressure that a digester can guarantee is no longer an additional advantage. Therefore, a fixed-dome digester is chosen. This digester has the simplest construction of the three potential digesters, has no moving parts, is easy to maintain and has a long lifespan. The fixed-dome digester has been chosen instead of the hydraulic digester because the fixed-dome digester has the simplest construction of the two. The floating-drum digester has moving parts, which require more maintenance and have a shorter lifespan.

4 Design of the fixed-dome digester

The fixed-dome digester is one of the simplest and most common digesters in developing countries as has been discussed in the previous chapter. However, there are different (standard[2]) types of fixed-dome digesters such as the Chinese fixed-dome digester, Deenbandhu fixed-dome digester, the Camartec fixed-dome digester and the Akut fixed-dome digester. Each of these digesters has a dome-shaped top. However, these digesters differ mainly in the shape of the bottom, but there are many more possibilities than these standard models of fixed-dome digesters. A description of these models will give an idea of the possibilities [20].

4.1 Fixed-dome digesters

In this section, several standard fixed-dome digesters are discussed in order to create an overview of the possibilities.

4.1.1 Chinese fixed-dome digester

The Chinese fixed-dome digester is the foundation of all the fixed-dome digester types. This digester is the first type of fixed-dome digester designed. As a result, all the other fixed-dome digester types are based on this design. The digester consists of a cylinder with a spherical bottom and top, this is shown in Figure 4-1. The original Chinese fixed-dome digester had a PVC inlet and outlet, but these can also be made out of concrete [20].

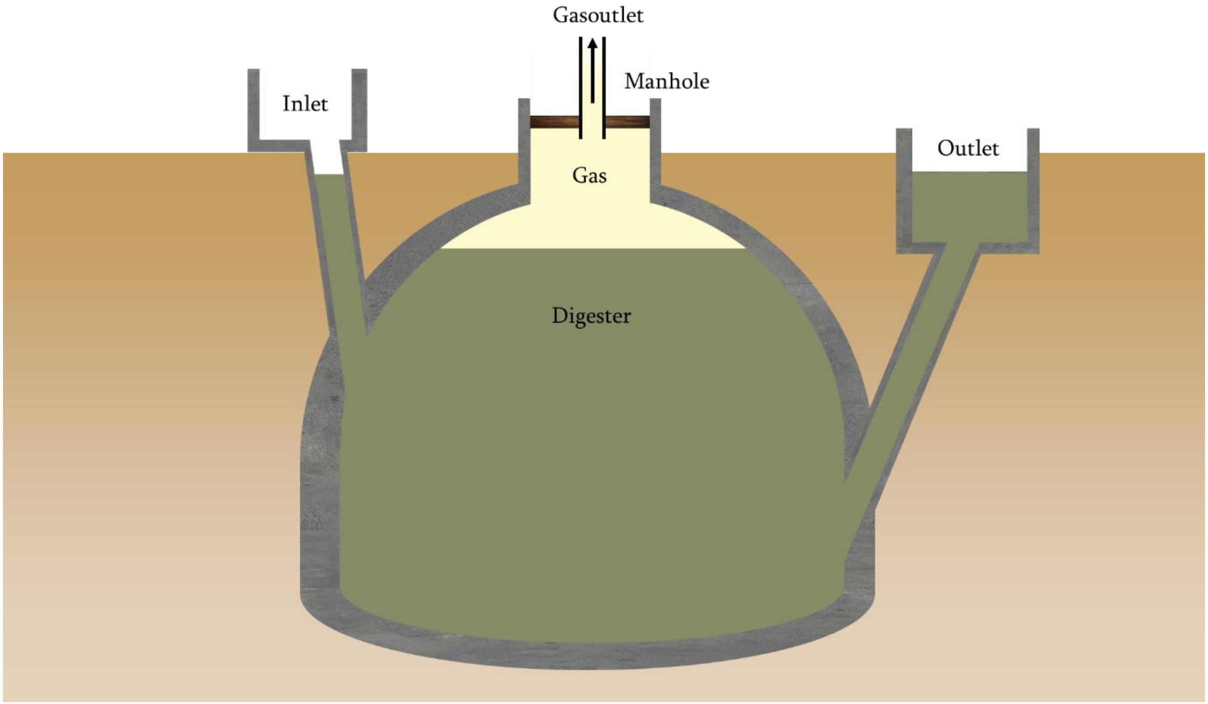

Figure 4-1: Chinese fixed-dome digester [21]

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[2] By "standard" types of digester is meant that these designs of the fixed-dome digester are common.

4.1.2 Deenbandhu fixed-dome digester

The Deenbandhu model has a spherical top and a spherical bottom. The digester is usually made of ferrocement. The plant can have either a rectangular overflow tank or a dome-shaped overflow tank as shown in Figure 4-2.

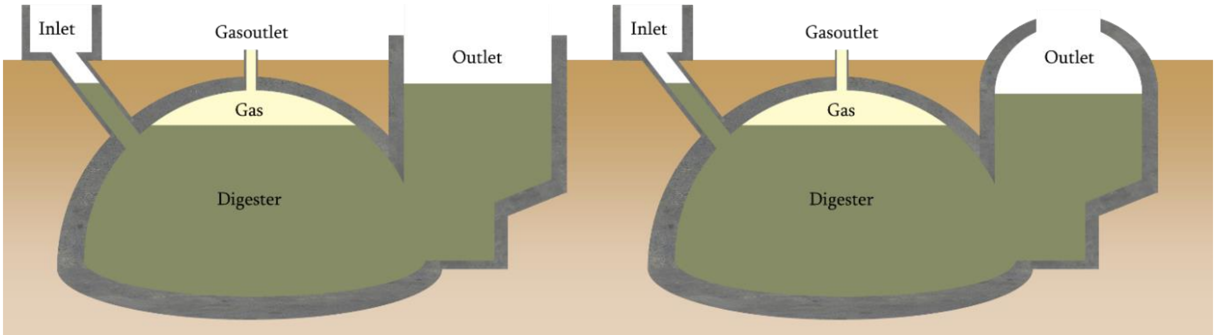

Figure 4-2: Deenbandhu fixed-dome digester with different overflow tanks [20]

4.1.3 Camartec fixed-dome digester

The Camartec model has a relatively simple design, consisting of a dome-shaped top placed on a flat base, this design is shown in Figure 4-3. The disadvantage of the flat bottom is that it has a lower load-bearing capacity and is, therefore, less structurally stable than, for example, a conical or spherical bottom. Therefore, the Camartec model requires a more solid foundation in comparison to other models, which results in a higher cost [20].

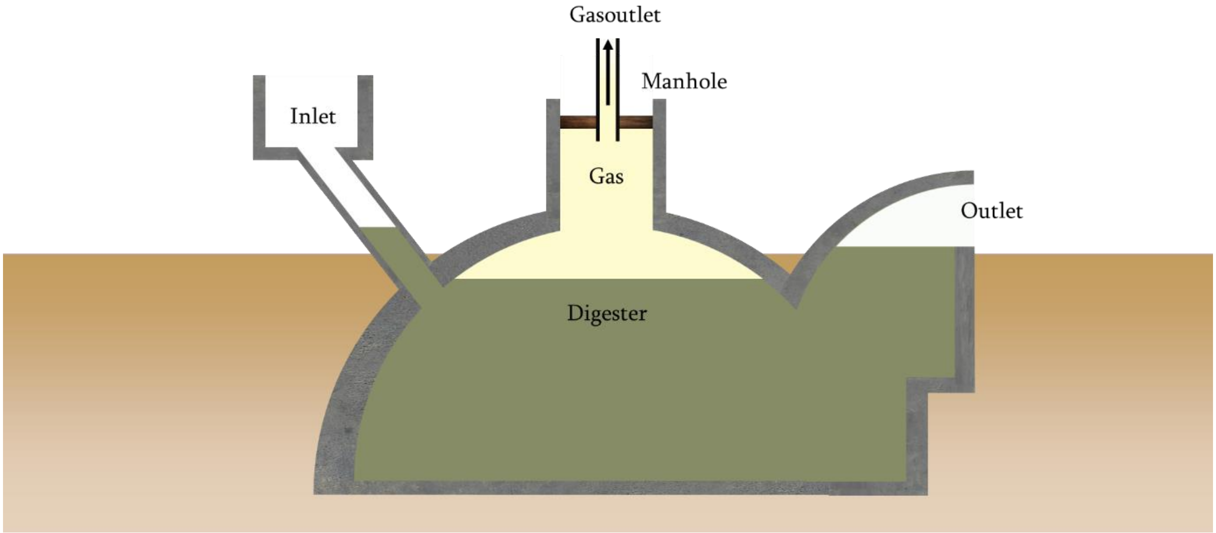

Figure 4-3: Camartec fixed-dome digester [20]

4.1.4 Akut fixed-dome digester

The Akut model has a cylindrical digester with a dome-shaped top and conical bottom. The overflow tank of this model is rectangular. The design of an Akut model is shown in Figure 4-4.

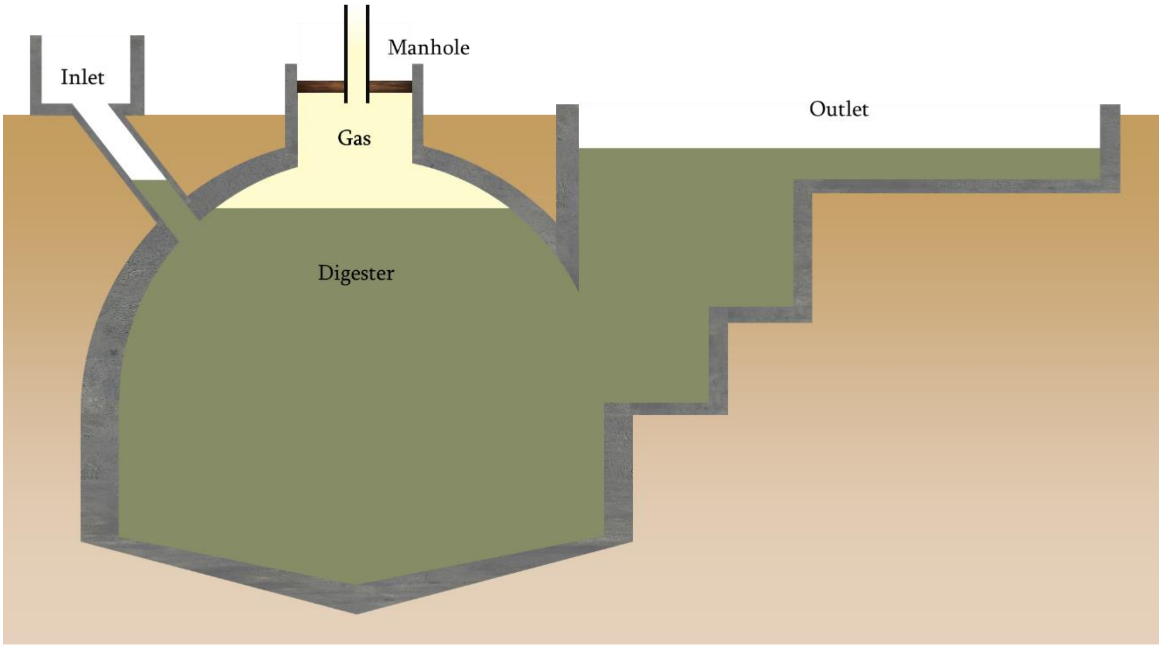

Figure 4-4: Akut fixed-dome digester [22]

4.2 Inlet and outlet of the digester

The inlet and outlet are also important parts of the biogas installation. These are discussed below.

4.2.1 Inlet reservoir

The biomass is brought into the inlet reservoir after the pre-treatment process. The primary function of the inlet is to store biomass. However, the biomass can also be dried and heated in the inlet reservoir during the day. Other functions that can be performed in the inlet reservoir are mixing the biomass and adding water. Solids such as gravel sink to the bottom of the inlet reservoir. These solid parts should be removed as much as possible in advance because they sink to the bottom in the digester and take up useful space. This reduces efficiency and can clog the pipes. To prevent the settled solids from ending up in the filler pipe, the inlet of the filler pipe should be 3-5 cm higher than the bottom of the inlet reservoir [23]. In this way, some of the solid particles are filtered out of the biomass.

The construction of the inlet reservoir is quite simple. The inlet reservoir for biogas installations often consists of a concrete cylinder (Figure 4-5). The inlet reservoir can also be made of another material. The bottom of the inlet container can be placed under a slight slope (sloping towards the filler pipe). It is recommended that the opening of the filler pipe is sealed so that the biomass does not flow directly into the digester. The biomass can then be stored in the inlet tank for as long as desired, for example, to dry the biomass or to precipitate the solid particles [20].

Figure 4-5: Examples of an inlet reservoir

4.2.2 Inlet pipe

The inlet pipe connects the inlet tank to the digester. It is important that the position of the inlet pipe is correct to avoid problems such as biomass backflow, clogging or gas leakage. To begin with, the inlet pipe should be straight. This lowers the chance of blockages and any blockages can be removed with a stick. If it should be possible to stir or poke into the biomass with a stick, the extension of the centerline of the inlet pipe should point approximately to the center of the bottom of the digester [23]. The opening of the filler pipe on the side of the inlet tank must be higher than all the other openings to the atmosphere. If this were not the case, backflow of the biomass could occur. This means that the biomass in the digester can run back into the inlet reservoir. The end of the filler pipe should not be positioned too close to the bottom of the tank to prevent blockage by solid and granular soil material. It is also best that the filler pipe does not extend too far into the digester and is certainly not placed in the gas compartment, as gas could then flow out via the filler pipe [24]. The retention time of the biomass in the digester is affected by the position of the inlet. If the inlet ends exactly at the inner wall of the digester, circular liquid patterns are formed, giving the biomass a longer retention time. In contrast, a ray-shaped pattern is formed if the tube extends far from the wall of the digester. This provides a longer retention time [20]. An example of good and bad positioning of the filler pipe is shown in Figure 4-6.

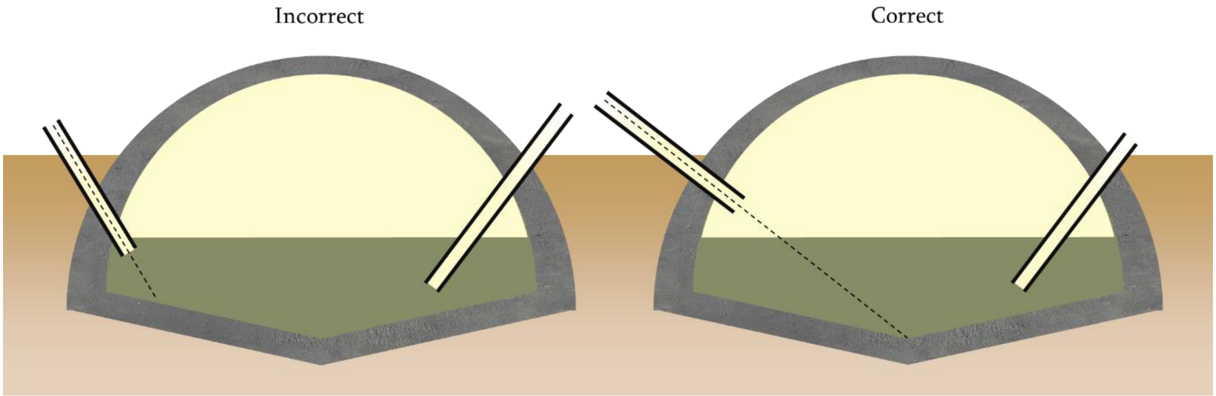

Figure 4-6: Example of incorrect and correct positioning of the inlet pipe

4.2.3 Stirring installation

The purpose of stirring and poking in the digester is to mix the fresh biomass with digestate and thus inoculate the fresh material with microbes. This mixing avoids temperature gradients in the digester and also prevents foaming [9]. Large industrial biogas installations are often equipped with special stirring systems. For domestic biogas installations stirring with a stick is the simplest and safest method [23]. Usually, there is no stirring at all in these smaller biogas installations. In a continuous digester, biomass is fed daily, creating natural mixing. This is usually sufficient. From the results of a small-scale test setup (Figure 4-7) that included testing the effect of a stirring system, it could be concluded that stirring the biomass does not affect biogas production [3].

Figure 4-7: Small scale digester (test setup)

4.2.4 Digestate storage

The overflow tank can also serve as digestate storage, but a separate digestate storage can also be used, which is connected to the overflow tank. As post-treatment of the digestate, drying and composting of the digestate is chosen, this post-treatment is simple but sufficient. An elongated, rectangular reservoir allows the digestate to spread across the reservoir and be dried by the sun and so that the temperature of the digestate is as high as possible to inactivate the pathogens as much as possible (see section 7.2)

4.3 Criteria for choosing the design

In this section, various criteria are discussed with regard to the digester. Based on these criteria, the final design can be decided.

4.3.1 Design and shape of the digester

A well-founded installation can withstand high external loads and high internal pressure, resulting in a longer lifespan with fewer repairs, making the installation more cost-effective. A dome shape can carry heavier loads than a flat plate of the same material with the same thickness. This principle is shown in Figure 4-8.

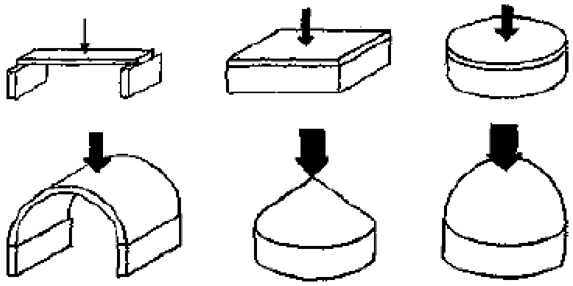

Figure 4-8: Shape in relation to the carrying capacity, the thicker the arrow the greater the carrying capacity [23]

Because of the flat bottom, the Camartec model is less robust. The Chinese model and the Akut model have a cylindrical digester with a dome-shaped top. The cylindrical digester makes these models less robust because a cylinder is mechanically weaker than a dome. The Deenbandhu model is the strongest and most robust design because it has a dome-shaped digester. Regardless of the design, a well-designed and constructed plant will have a long lifespan. But if all the mentioned models are constructed with the same quality and materials, the Deenbandhu model will be the most structurally stable and will have the longest lifespan [20]. However, it is important to note that the lifespan of a well-maintained installation is naturally higher than that of a not-maintained installation, regardless of its design.

4.3.2 Design of the manhole

The manhole gives access to the digester, in order to repair or clean the digester so that solids can be removed. The Chinese, Camartec and Akut models have a manhole at the top. The disadvantage of a manhole at the top is that the strength of the dome decreases. Another disadvantage is that the manhole must be sealed gas-tight to prevent a gas leak. The Deenbandhu model is designed in such a way that the digester can be entered through the overflow tank. In this way, the digester can easily be entered while maintaining the strength of the dome. Existing Deenbandhu installations also have the least problems in terms of gas leaks. This is due to the absence of a manhole in the dome. It can therefore be concluded that a sufficiently large opening in the overflow tank is sufficient. Also, an additional hole in the dome increases the risk of gas leaks and introduces a new weak point in the structure [20]. When designing and sizing the manhole, safety must be taken into account. The hole must be large enough to ensure sufficient ventilation and a person must be able to enter and exit the digester with sufficient comfort.

4.3.3 Design and shape of the bottom

The bottom of the digester carries the weight of the digester, the weight of the biomass in the digester, and the weight of the soil above the digester. The bottom further distributes this weight over the soil below the digester [23]. A spherical bottom, such as the one from the Deenbandhu and the Chinese model has the greatest load capacity, the disadvantage of this is that a spherical bottom is difficult to construct. An alternative is a conical bottom, this has a slightly smaller load capacity, but is easier to construct. The bottom of the Camartec model is flat and therefore has the smallest load capacity, but is the easiest to construct [20].

4.3.4 Overflow tank and outlet pipe

The outlet pipe and the overflow tank are two important components of a biogas installation. The overflow tank can be connected to the digester via an outlet pipe, but it can also be connected directly to the digester, this is the case for example in the Deenbandhu model. The outlet must be located below half of the digester, otherwise too much and too fast fresh biomass flows out of the digester, which can reduce gas production by 35% [23]. In the Deenbandhu model, the hole connecting the overflow tank to the digester is designed so that the digester can be easily accessed through this hole. This hole also allows the use of fibrous and foam-forming biomass such as offal. This is not the case with other fixed-dome models. The overflow tank can be rectangular or dome-shaped, a rectangular reservoir is easier to construct [20].

4.3.5 Ease of maintenance

A well-designed and built structure does not require frequent maintenance, but it cannot be avoided no matter how well a biogas installation is designed. A biogas installation usually needs to be emptied and possibly painted once every five years due to the increasing number of stones and other solid parts that accumulate in the digester. These take up useful space in the digester and therefore reduce the gas yield of the digester [20]. Maintenance is done through the access hole. If the access hole is in the dome, the digester must be maintained and emptied through this hole, this makes maintenance extra labor-intensive and difficult. Emptying the digester also requires more than one person. Before maintenance can be done, the seal of the access hole must be removed. After maintenance, the access hole must be sealed airtight again. Thus, it can be concluded that maintenance, if the access hole is located in the dome, is cumbersome and labor-intensive [20].

In the case of the Deenbandhu model, maintenance is easier. The digester can be accessed through the overflow tank and emptying the digester is less labor-intensive and can be done by one person [20].

4.3.6 Lifespan of the digester

The average lifespan of the fixed-dome models is about the same (20-25 years). The construction technique and the quality of the materials used are important factors that contribute to the lifespan. The Deenbandhu model has the longest lifespan because it is the most structurally stable of all the models. But existing installations show that all the discussed models are durable and reliable and have a long lifespan of more than 20 years [20].

4.3.7 Building the installation

The bottom of the Camartec model is the easiest to construct because it is flat. The Deenbandhu and Chinese models have spherical bottoms, making the bottoms of these models more difficult to construct. The bottom of the Akut model is conical making it more difficult to construct than a flat bottom but easier than a spherical bottom. This spherical or conical bottom makes it more difficult to construct the rest of the digester on top of it [20]. The dome of the Deenbandhu model can be made entirely with bricks. A support should be placed in the dome to finish the top of the dome, this makes it more difficult to build the dome. Because bricks are used no formwork is required, which makes building the Deenbandhu model with bricks easier [25]. All fixed-dome models must be plastered with mortar and painted with airtight paint. As a note, the cylindrical structure on which the access hole is located, as shown in Figure 4-1 and Figure 4-3, does not necessarily have to be present [20].

4.3.8 Choice of fixed-dome digester

Table 4-1 shows the main characteristics of the different types of digesters. It follows from this table that the Deenbandhu model has the most advantages for almost all of the criteria discussed.

Table 4-1: Overview of the main features of the different types of fixed-dome digesters

Type	**Mechanical properties and structural stability**	**Maintenance**
Chinese model	• Less structurally stable due to the cylindrical digester • Spherical bottom is the strongest bottom • Access hole in the dome introduces weak point • Most difficult construction of the bottom	Maintenance through the access hole in the dome: • Chance of gas leak in the access hole • Labor-intensive • Emptying requires more than one person • After maintenance, the access hole must be sealed gas-tight
Camartec model	• Less structurally stable because of the flat bottom • Access hole in the dome introduces weak point • Easiest construction of the bottom	
Akut model	• Less structurally stable due to the cylindrical digester • Strong conical bottom • Access hole in the dome introduces weak point • Construction of the bottom is easier than the spherical bottom	
Deenbandhu model	• Most stable model due to spherical bottom and dome • No access hole in the dome • Longest lifespan • Most difficult construction of the bottom	Maintenance via the overflow tank: • Emptying can be done by one person • Less labor-intensive

In summary, the Deenbandhu model is the most structurally stable because of its spherical bottom, its dome, and the lack of an access hole in the dome. This structural stability ensures that the Deenbandhu model has the longest lifespan of all the models discussed and the least chance of gas leaks from cracks that might appear over time. Another great advantage of the Deenbandhu model over the other models is that this model is much more maintenance-friendly. Emptying the digester can be done by one person and is less labor-intensive because the digester does not have to be emptied through a hole at the top of the dome but through a hole about halfway up the dome. The digester can be accessed through the overflow tank, on contrast to the access hole from the top of the dome in the other models. The Deenbandhu can, as mentioned earlier, be equipped with a dome-shaped or rectangular overflow tank, the rectangular reservoir is more simple in construction but the dome-shaped overflow tank can withstand higher loads and pressures and is therefore more structurally stable. Since the overflow tank is not subject to high pressures or loads, a rectangular tank is chosen because it is more simple in construction. The disadvantage of the Deenbandhu model is the difficult construction of the spherical bottom, however, this can be solved by using a conical bottom, which still has a large load-bearing capacity but is easier to construct than a spherical bottom. For the installation a modified Deenbandhu digester with a conical bottom and a rectangular overflow tank is chosen, this design is schematically shown in Figure 4-9.

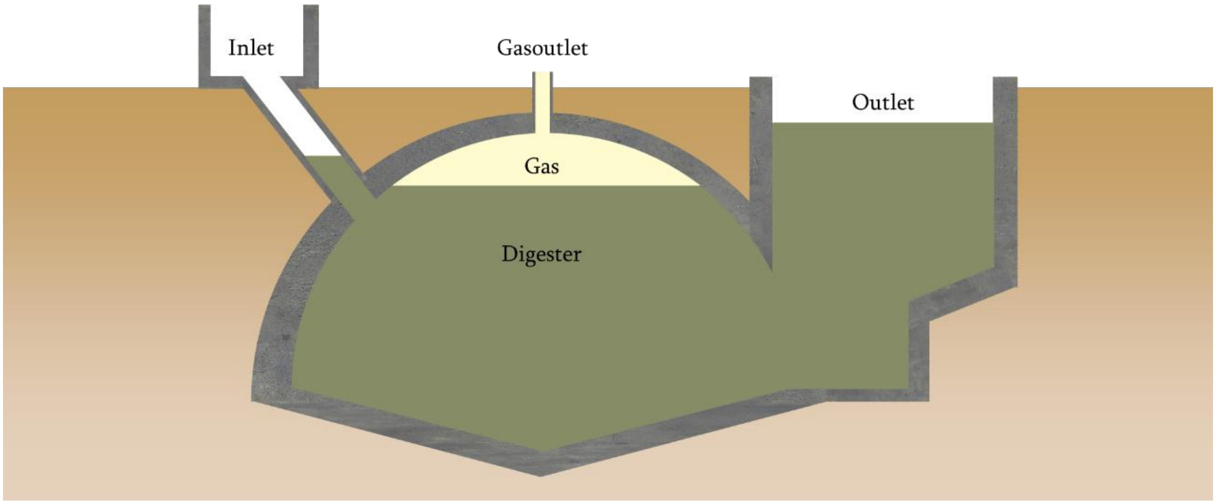

Figure 4-9: Modified digester design

5 Overview of gasholder technologies

An important part of the biogas installation is the gasholder. A gasholder can be located above (built into) the biogas installation or can be provided separately. Biogas can be stored for a longer period of time in a gas-tight container without losing their energy content. This is a clear advantage over other renewable energy sources such as solar or wind power, which must be consumed immediately (unless energy is stored in a battery). A disadvantage of biogas is its relatively low energy density: 1 m^3 of biogas corresponds to only 0.6 to 0.7 liters of fuel oil (6 kWh). If biogas is not compressed, it needs a large storage volume. All gasholders must be gas-tight and pressure-resistant. In addition, all types of storage facilities that are not located in a building must be UV, temperature and weather resistant. The simplest way to store biogas is in low-pressure systems. These low-pressure systems can be separate gasholders, but also the gasholders built into the discussed digesters are low-pressure systems. Section 3.2 has already discussed where and how the gas is stored in the different types of biogas installations if the gasholder is located above the biogas installation. These previously discussed gas storage will therefore not be discussed further in this chapter [9].

An external gasholder has the advantage that more biogas installations can be connected to it and that if the biogas installation is maintained there is still a supply of gas. An external gasholder is usually built if the produced gas has to be transported over long distances or to buffer the difference between production and consumption. The production of biogas varies during the day, depending on the feeding pattern and changes in ambient temperature (this variation is usually negligible and will also be neglected in this paper). Moreover, gas production continues at night. This means that the production and consumption of biogas often do not take place at the same time [9]. Depending on the design of the gasholder, constant gas pressure can be guaranteed. A disadvantage of a separate gasholder is that an external construction is required. This involves extra costs. In addition, the entire installation takes up more space [24].

The size of the gasholder depends on the gas production and how often and how much gas is consumed. For example, if TUM's kitchen is not used at the weekend, the gasholder must be able to store at least the volume of biogas produced in two days.

5.1 Low-pressure gasholder

In this section, different types of low-pressure gasholders are discussed.

5.1.1 External balloon gasholder

The external balloon gasholder consists of a balloon-like construction (shown in Figure 5-1 and Figure 5-2). The gasholder is similar to a big balloon inflated by gas. The gasholder consists of a plastic bag similar to the balloon-type digester. If necessary, support poles can be provided to keep the bag straight. The desired gas pressure can be obtained by adding extra weights to the gasholder. This gasholder has a low construction cost and gives a visual indication of the amount of gas stored. In order to keep the cost of the gas storage as low as possible, it is best to produce them locally. If the balloons have to be imported, the cost increases considerably. The disadvantage of this gas storage is that the construction is sensitive to mechanical damage and that extra weights are often required on the balloon when the gas pressure is low [24]. The material must be gas-tight, UV-resistant, flexible and strong. PVC is not suitable. The weakest points of these bags are the seams, especially the connections between the plastic foil and the pipes. The balloon can be laid on sand beds or hung up. It may also be necessary to protect the bags from rodents. In addition, the gas pressure must be kept within safe limits by means of a safety valve. By doing this the maximum tension in the weakest points of the balloon is not exceeded [9].

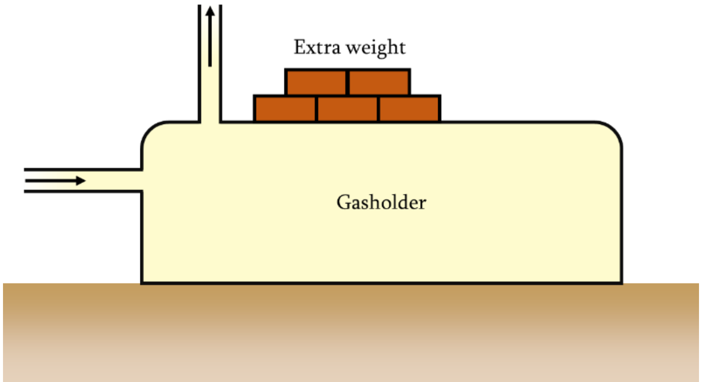

Figure 5-1: Schematic representation of an external balloon gasholder

Figure 5-2: Gas storage bag from Spacebladder [26]

5.1.2 Gasholder with water basin

The gasholder with water basin consists of a metal cylinder placed in a concrete cylinder filled with water (shown in Figure 5-3). The metal cylinder floats on the water in the concrete cylinder [24]. The gas is stored between the water and the metal cylinder. Constant gas pressure can be guaranteed by the rise and fall of the metal cylinder. This gas pressure can be regulated by attaching weights to the top of the metal cylinder. A structure is needed to keep the metal cylinder in balance, for instance, an external frame. The height of the metal cylinder gives a visual indication of the amount of gas stored. The disadvantage of this construction is that the metal drum is susceptible to corrosion and that this external gas storage involves additional construction costs. However, the drum can also be made from different materials like, fiber-reinforced plastic, which is not prone to corrosion.

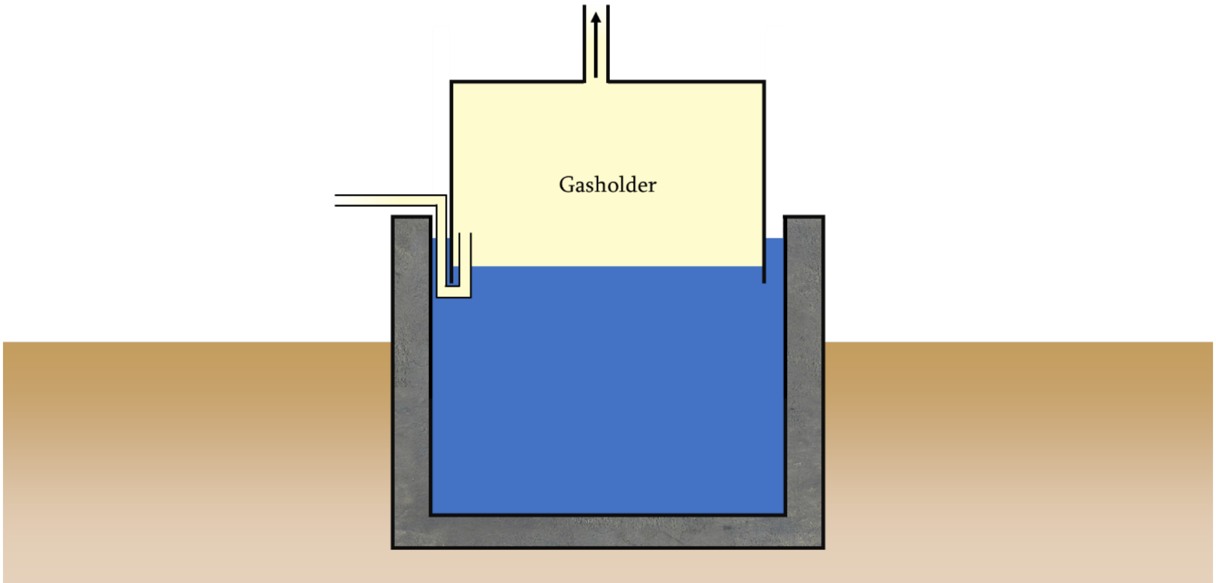

Figure 5-3: Schematic representation of a gasholder with water basin

5.1.3 Floating-drum gasholder

This type of gasholder has much in common with the gasholder of the floating-drum digester. The gasholder consists of two concentric cylinders in the ground. These cylinders are usually made of concrete. The opening between the two cylinders is filled with water. A metal drum is placed between the two cylinders and floats on the water [3]. A schematic representation of the floating-drum gasholder is shown in Figure 5-4.

The produced biogas collects in the gas drum and pushes the drum upwards. This gas drum can rise or fall depending on gas production and gas consumption. The level of the drum is thus a visual indication of the available quantity of gas. Constant gas pressure can be guaranteed by the rise and fall of the (metal) drum. The weight of the drum applies pressure to the gas in the drum. This creates a certain gas pressure that is approximately constant, regardless of the amount of gas in the drum. This gas pressure is sufficient to operate a normal gas fire. If higher gas pressure is required, the higher pressure can be obtained by placing additional weights on the drum. In a gasholder with a floating drum, a safety valve is not necessary. If the drum becomes too full, the excess gas can escape because the edges of the drum are briefly above the water [9]. The advantages and disadvantages are mainly the same as those of the floating-drum digester. In short, the main advantages are: constant gas pressure and the height of the drum is an indication of the gas pressure. The main disadvantages are: the lifespan is lower than that of the fixed-dome digester itself (when a metal drum is used), the drum consists of corrosion-sensitive parts (when made out of metal) and has to be repainted regularly (when made out of metal). The difference with the gasholder with water basin is that with the floating-drum gasholder, only the space between the two concentric concrete cylinders is filled with water.

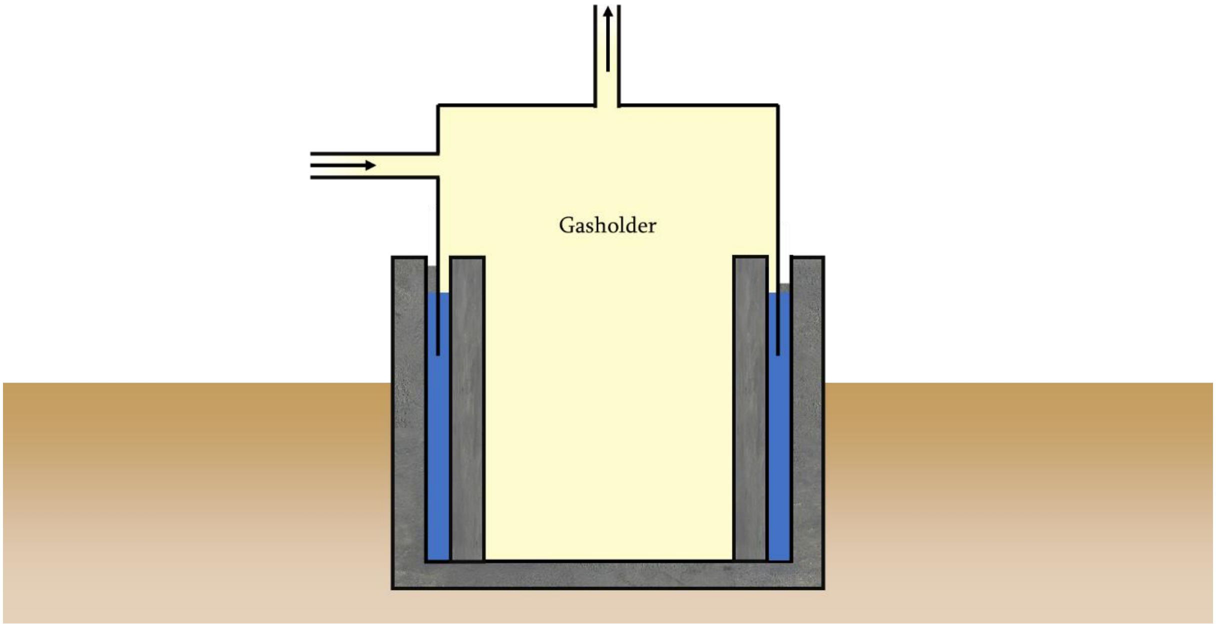

Figure 5-4: Schematic representation of the floating-drum gasholder

5.2 Medium pressure gasholder: gas storage tank

A gas storage tank (example shown in Figure 5-5) is the most suitable gas storage system if biogas is stored at a medium pressure of 5-20 bar. Because the biogas is stored under higher pressure and therefore has a higher energy density, a larger amount of energy can be stored in a smaller space than with low-pressure gas storage tanks. At a gas pressure of 10 bar, 10 times more biogas can be stored than with low-pressure gasholders. This pressure can be achieved with a single-stage compressor. An additional requirement is that a pressure regulator is needed for the gas outlet. The major disadvantage of this installation is that a compressor is required, which is an additional investment. An added disadvantage of the compressor is that with a gas reservoir of 10 bar, an energy requirement of approximately 0.22 kWh/m³ must be taken into account [9]. Because of these drawbacks, it is not always possible to install a compressor in developing countries.

Figure 5-5: Gas storage tank with a pressure of 10 bar [9]

5.3 High-pressure gasholder: gas bottle

When storing biogas at high pressure, biogas is compressed to over 200 bar and stored. The storage is technically feasible in gas bottles (an example is shown in Figure 5-6). When storing biogas at high pressure, it is necessary to purify the biogas of hydrogen and H_2S in order to prevent corrosion of the gas cylinders. This option is only feasible for large biogas installations due to the high costs. The purification of biogas also has the advantage that the methane concentration increases from an average of 60-65% (unpurified) to 90% (purified) [27]. About 20% of the biogas (1- 1.5 kWh/m^3 gas) is needed to drive the compressor. Biogas bottling in developing countries is also not yet implemented on a large scale [9]. Due to the mentioned disadvantages, high-pressure gas storage is not a possibility in developing countries.

Figure 5-6: Gas bottle for biogas storage [28]

5.4 Choice of gasholder

An external gasholder is chosen to buffer the difference between consumption and production. In this way, more gas can be stored than in an integrated gasholder. The advantages and disadvantages of the discussed external gasholders are shown in Table 5-1.

Table 5-1: Advantages and disadvantages of the different types of external gasholders

Type	**Advantages**	**Disadvantages**
External balloon gasholder	• Low construction cost • Visual indication of the gas content	• May have to be imported • Sensitive to mechanical damage • Extra weights are often required • Bags may have to be protected from rodents • Safety valve's
Gasholder with water basin	• Constant gas pressure • Visual indication of the gas content • Drum can be made from a material not prone to corrosion • Safety valve is not necessary	• Structure is needed to keep the metal cylinder in balance • Metal drum is susceptible to corrosion
Floating-drum gasholder	• Constant gas pressure • Visual indication of the gas content • Drum can be made from a material not prone to corrosion • Safety valve is not necessary	• Metal drum is susceptible to corrosion
Gas storage dank	• Higher energy density • Biogas can be stored in a smaller space • Longest lifespan	• Compressor is needed
Gas bottle	• Higher energy density • Biogas can be stored in a smaller space • Longest lifespan • Higher methane concentration	• Compressor is needed • Biogas has to be purified

A low-pressure gasholder is chosen. The main disadvantage of the medium-pressure and high-pressure gasholder is that a compressor is required. A compressor is a big extra cost and requires electricity and therefore consumes energy. As mentioned before, the project serves as a pilot installation. The biogas installation will be disseminated over local communities and schools in the two-year project. It is therefore important that the technologies used remain low-tech and accessible. A compressor would interfere with this objective.

The aim is a gasholder with a lifespan similar to that of the fixed-dome digester. For this reason, the external balloon gasholder has not been chosen. Moreover, the external balloon gasholder does not provide biogas at constant pressure. The two remaining options are the floating-drum gasholder and the gasholder with water basin. As mentioned earlier, the floating-drum gasholder floats between two concentric cylinders. The drum of the gasholder with water basin simply floats in water in one cylinder. Therefore, the drum of the floating-drum gasholder is more stable. In addition, the floating-drum gasholder requires less water. For these reasons, the floating-drum gasholder is chosen. This gasholder is further described in section 9.4.

6 Hybrid biogas installation

As mentioned earlier in section 3.1.3, a hybrid plant will be designed. In this way, higher efficiency is obtained. The design of the hybrid system is discussed in this chapter. The first objective of the hybrid installation is to eliminate the disadvantages of the fixed-dome installation. But a second reason for the hybrid installation is that it will serve for educational purposes. A hybrid plant makes it possible to investigate the efficiency of the different systems of which the hybrid plant consists, which is very interesting for educational purposes. Besides, fixed-dome digesters have no recent innovations, despite their biggest flaw e.g. its low efficiency [29]. Expanding a fixed-dome installation to a hybrid installation is the first step towards innovative fixed-dome biogas installations.

6.1 Disadvantages of a fixed-dome installation

The main purpose of the hybrid installation is to largely eliminate the disadvantages of the fixed-dome installation and to increase efficiency. The main problem of the fixed-dome system in practice is its low efficiency. This problem is not sufficiently discussed in overview papers. The low efficiency comes up again and again when enquiring about the disadvantages of the fixed-dome system with specialized and competing companies and research institutions. Examples of such organizations in Kenya are chronological Mtwapa Energy Center, Flexi Biogas Solutions and Pwani University. During an internship at Pwani University, with Prof. Rewe Thomas as a mentor, a lot of knowledge was gained in the disadvantages of a fixed-dome installation [29]. Other disadvantages are gas pressure fluctuations (which complicated the usage of the gas), a high gas pressure, the gas content in the digester is not visible and the development of cracks in the digester, especially in the build-in gasholder cause gas leakage. Also, the digestion temperatures are on the low side, resulting in low gas production and thus lower efficiency, which was mentioned earlier. The problems concerning the gas storage are solved by using the external gasholder discussed in section 5.4. In order to prevent the cracks, an experienced biogas technician should (and will in this project) help with the supervision of the construction [20], [30].

The slurry coming out of the plant has undergone a relatively incomplete digestion process. In other words, this slurry still has potential for gas production. As a result, gas production still takes place in the overflow tank and in the digestate storage tank. Due to the hydraulic operation of the fixed-dome installation, a lot of fresh biomass enters the overflow tank. This fresh biomass causes a relatively large amount of biogas production in the overflow tank. This biogas is not collected and can therefore be seen as a loss, but also as great potential to increase efficiency. The gas production in the overflow tank and digestate storage can be seen with the naked eye as bubbles in the slurry. In the designed installation (discussed in section 0) and other fixed-dome installations, this gas production is not captured. As a result, greenhouse gas emissions are released into the atmosphere. In addition to these greenhouse emissions, there are also emissions of ammonium, fugitive losses of methane and the escape of odors [31].

6.2 Additional installation(s) for the hybrid biogas installation

In order to overcome the disadvantages of the fixed-dome installation, common biogas technologies in Kenya are being examined. In this way, the hybrid installation will be more relevant in Kenya and more knowledge about the technology can be obtained. In Kenya, there are mainly 3 types of digesters: fixed-dome, floating-drum and balloon-type digesters [32]. Originally (starting from 1970) only the fixed-dome and floating-drum digester were installed in Kenya [33], but now (2021) the Kenya biogas program is also promoting and supporting balloon-type digesters, therefore balloon-type digesters are becoming more common in Kenya, especially in newer installations. The most common balloon-type digester used in Kenya is a flexi biogas installation and is one of the most recent innovations concerning biogas in Kenia. Flexi biogas installations in Kenia are mainly made and distributed by the company 'Flexi biogas solutions' [7], which also have patents on various flexi biogas technologies.

The first problem that will be tackled is the gas losses in the overflow tank (and the other disadvantages such as greenhouse gas emissions that result from the loss of gas). This problem can easily be solved by covering the overflow tank. By doing this the additional gas produced in the overflow tank will be captured and thus increasing the gas production and efficiency of the installation.

The efficiency can be further increased by placing another biogas installation in series with the fixed-dome installation. As mentioned in section 3.2.3, the balloon-type digester has a high efficiency and a complete digestion process. Besides these advantages, the flexi biogas installation (which is a balloon-type digester) is one of the most common new biogas technologies in Kenya. This installation can be purchased prefabricated at a low cost compared to other biogas technologies. Since the flexi biogas installation and the fixed-dome plant are common in Kenya, it is interesting to show the potential of combining these technologies. In addition, the flexi biogas installation solves some disadvantages of the fixed-dome plant: the low efficiency and the incomplete digestion process.

The flexi installation is considered to be installed in series with the fixed-dome installation (the final design is discussed in section 6.7. The flexi installation is suitable because of the (discussed) advantages of the flexi installation (as an additional biogas installation).

The cover of the overflow tank will be made by the company 'Flexi Biogas Solutions'. This because the company has already made such covers (for the test setup described in section 6.4).

6.3 Flexi biogas installation

A flexi biogas installation is a balloon-type digester, and one of the most recent innovation concerning biogas in Kenia, according to Flexi Biogas Solutions [15]. The flexi biogas installation is a practical, affordable, flexible and easy to construct biogas technology. *Affordable:* To get an idea of the cost of such an installation, the cost of a flexi biogas installation with a feeding ratio of 40-60 kg a day from the company 'Flexi Biogas Solutions' costs around € 900, including a gas stove and construction of the biogas installation. *Practical:* The materials used for the digester are light and foldable, this means that the digester can be moved reasonably easily. The digester can also be packed very compact in order to transport it, as shown in Figure 6-2. *Ease of construction:* The installation requires no digging, masonry and other heavy labor-intensive work, as seen in Figure 6-2. *Flexible:* Several flexi biogas installations can be placed in series, without interrupting the digesting process, this means when a bigger biogas installation is needed, more flexi biogas digesters can be placed in series, without the need of fully dismantling the already present setup [16].

Figure 6-1: Example flexi biogas installation [16]

Figure 6-2: Transport of the flexi biogas kit [16]

6.3.1 The construction

The flexi biogas installation consists out of 3 main parts: the balloon, the UV filter and the net. *The balloon* is the digester itself and also functionates as a gasholder. It can also be seen as a bag that can be opened via the green lip, shown in Figure 6-1. The lip is a zip-like seal and is present at both ends of the balloon. The digester can easily be emptied true these lips. *The UV filter* (the greenhouse fabric) protects the balloon against UV radiation in order to expand its lifespan. *The net* offers protection against mechanical damage like a puncture. The UV filter and the balloon can be seen inside the micro-greenhouse tunnel, shown in Figure 6-3. The net and the UV filter form the tunnel. The tunnel helps to keep the temperature high (around 40°C for the climate in Mombasa) which is near-optimal temperature. The tunnel captures heat during the day and therefore increases the temperature of the substrate inside the balloon and during the night the tunnel acts as an isolation jacket to prevent heat losses. By keeping the temperature high, gas production is kept high. The greenhouse tunnel has to be replaced approximately every 5 years [34].

Figure 6-3: Micro-greenhouse tunnel [16]

6.4 Existing hybrid biogas installation

This hybrid system is a unique system that can't be found in literature. The only similar system that has been built, was a temporary transformed fixed-dome biogas installation that functioned as a test setup. The test setup was located at Dream Children's Homes in Ngong, a small city near Nairobi, Kenya. This fixed-dome installation is shown in Figure 6-4. For the test setup, a balloon-like construction was placed on top of the overflow tank (3) and the digestate storage (4). The balloons capture the biogas that is still being released from the digestate and overflow tank. The gas production in the overflow tank and the digestate storage can be seen by the bubbling of the slurry. All the gas flows were measured with the test setup, the gas flow from the fixed-dome digester, the overflow tank and the digestate storage. The following results were obtained: 31.4% of the total gas flow is produced by the fixed-dome digester, 32.1% by the overflow tank and 36.5% by the digestate storage [35]. These results look verry promising for a hybrid system using a fixed-dome and flexi/flexible biogas installation. However, the results should be interpreted with caution. It can be expected that the composition and therefore the quality of the biogas from the 3 different tap points differ from each other. Therefore, the results obtained for the gas flow do not completely transfer to equivalent extra energy production. Nevertheless, higher efficiency and therefore more energy production is to be expected with a hybrid system.

Figure 6-4: Fixed-dome installation in Dream Children's Home. 1) inlet tank 2) digester 3) overflow tank 4) digestate storage

6.5 Quality of the digestate and the additional gas produced

As mentioned earlier the quality of the gas tapped from the different tapping points can differ from each other. To get an idea of the quality from the extra gas production (produced from the flexible digester placed in series with the fixed-dome digester), the quality of the fixed-dome output (digestate) should be studied.

The quality of the digestate is influenced by a number of parameters, such as temperature, pH, conductivity, concentrations of volatile fatty acids (VFA) and retention time of feedstock. Because of the dependence on all these parameters, the quality of the digestate cannot be theoretically determent [36]. In 'The biogas handbook Science, production and applications' the quality of the digestate is described as follows:

> Digestate has a lower dry matter content than the undigested influent: at least 50% of the dry matter content is converted to methane (CH_4) and carbon dioxide (CO_2). Furthermore, the content of ammonium-N (NH_4^+ –N) is high in digestate (around 20% higher than undigested cattle slurry) [36, p. 271].

The total solid content of the digestate can vary between 6-30% and depends on the digesting process [31]. The effect of the total solid content on the gas production can be seen in Figure 8-1. Deviations from the most optimal total solid content of 7.5% results in less gas production, therefore it can be concluded that the digestate has less potential for biogas production than the fresh feedstock. However, quantities of macronutrients, the micronutrients itself and the trace elements that are present in the digestate are the same as in the original feedstock [31], so these won't have an impact on the difference in gas production from the different tapping points.

As mentioned in section 6.1, 31.4% of the total gas flow from the discussed test setup is produced by the fixed-dome digester and 32.1% by the overflow tank. This means if the gas from the overflow tank is captured, according to the test setup double the gas is captured. However, as discussed earlier some properties and parameters of the digestate differ from the fresh feedstock. Therefore, the energetic value of the gas produced from the overflow tank can be lower than the energetic value of the gas produced from the fixed-dome digester.

6.6 Benefits of covering the digestate tank

During the digesting process, some organic nitrogen present in the substrate will be converted to ammonium. This higher ammonium concentration will result in higher ammonium emissions into the atmosphere. In order to prevent the emission of ammonium into the atmosphere, the digestate storage can be covered by a gastight cover (as discussed in section 6.2). This also has some additional benefits of capturing fugitive losses of methane, preventing the escape of odors and reducing greenhouse gas emissions [31]. An example of a gastight cover is shown in Figure 6-5. According to 'Biogas from Crop Digestion', "the additional biogas production, collected from digestate storage tanks, usually pays back the investments for covers within a short period of time" [31, p. 9]. The benefits discussed for covering the digestate tank also apply for covering the overflow tank in lesser degrees, because the digester output (digestate) mostly stays for a shorter period in the overflow tank than in the digestate tank. However, covering the digestate tank makes the daily accessing of the digestate tank more complicated and more time-consuming, while the overflow tank doesn't have to be accessed in normal circumstances.


Figure 6-5: Large scale digestate tank with a cover [31]

6.7 Types of hybrid biogas installations

Following previous sections, this part discusses different possibilities to achieve a hybrid design. This is done based on the various assumptions and boundary conditions of the previous sections. The installations always include the fixed-dome and can include a flexi type digester and a cover over the concrete overflow tank. In none of the discussed systems the digestate tank is covered, because the digestate has to be dried by the sun as described in section 4.2.4 and covering the digestate storage makes the daily accessing of the digestate tank more complicated and more time-consuming.

6.7.1 Option 1: Fixed-dome and flexi

The first option is shown in Figure 6-6 and consists out of a flexi biogas installation that is placed between the overflow tank and the digestate storage. As shown in Figure 6-6, the overflow tank is exposed to the open air. Thus the produced gas in the overflow tank is released into the air and lost. Also, the digestion process is interrupted because the slurry is exposed to the air. So only the extra gas produced in the flexi biogas installation is captured. The only adjustment this design requires is the addition of a flexi biogas installation. Therefore the flexi installation together with the extra piping is the extra cost of this hybrid system compared with the cost of a fixed-dome installation.

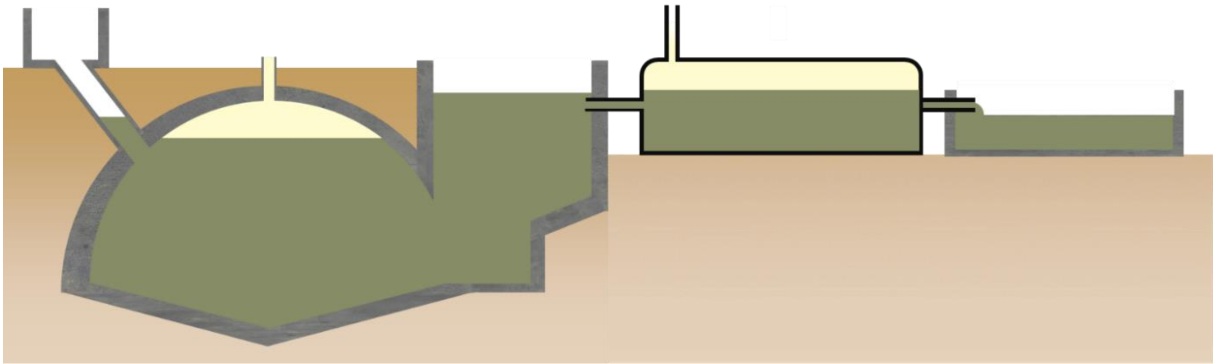
Figure 6-6: Conceptual drawing for the fixed-dome and flexi

In order to not interrupt the digestion process in the overflow tank, the overflow tank can be covered to prevent exposure from the slurry to the air, this is shown in Figure 6-7. However, the gas produced in the overflow tank is not captured. Therefore gas will accumulate in the overflow tank and the gas pressure in the overflow tank rises. In order to be able to enter the fixed-dome digester, a manhole needs to be added to the cover of the overflow tank or the cover has to be removable.

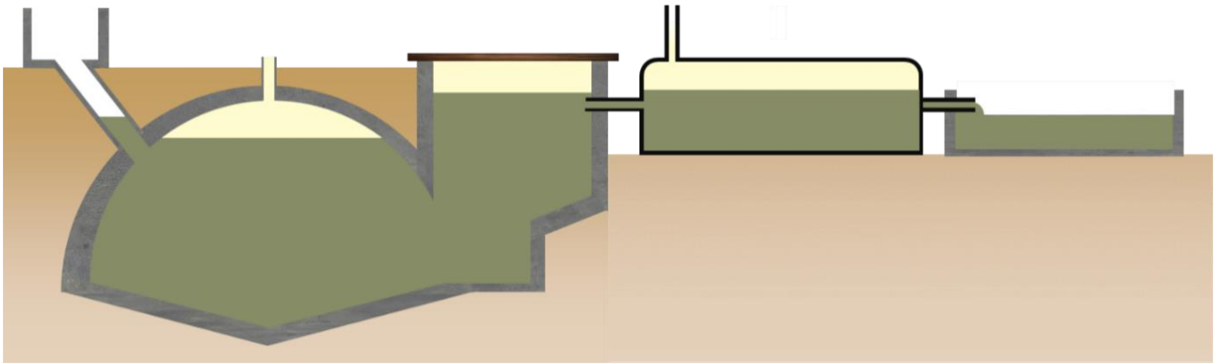

Figure 6-7: Conceptual drawing for the fixed-dome witch covered overflow tank (no gas collection) and flexi

6.7.2 Option 2: Fixed-dome with covered overflow tank and flexi

The second option is shown in Figure 6-8 and consists out of a flexi biogas installation that is placed between the overflow tank and the digestate storage and a cover placed over the overflow tank. The cover over the overflow tank captures the gas released and produced in the overflow tank. Because the overflow tank is covered, the digester can't be accessed through the overflow tank. Therefore some kind of manhole needs to be added to the cover. If the cover is rigged e.g. a concrete cover, a classic manhole can be added to the cover. If the cover is flexible it is possible to add a zip-like seal opening like in the flexi biogas installation. The flexi biogas installation increases the total digester volume when the size of the fixed-dome digester is kept the same and thus increasing the overall retention time and therefore producing more gas. In the hybrid installation the later digesting phases (taking place in the flexi biogas installation) are separated from the earlier digesting phases (taking place in the fixed-dome digester). Therefore a more complete digesting process can be expected in comparison with the fixed-dome digester. The slurry fed to the flexi biogas installation consists out of a mixture of different digesting phases. Thus it can be expected that the flexi biogas installation is not as efficient as a stand-alone flexi biogas installation. Because the installation has never been build before, the efficiency and the impact of the added parts in comparison with a stand-alone fixed-dome digester are unknown. These factors have to be measured and quantified when the installation is built. This captures the most biogas out of all the concepts and therefore has the highest efficiency, but also has the highest cost.

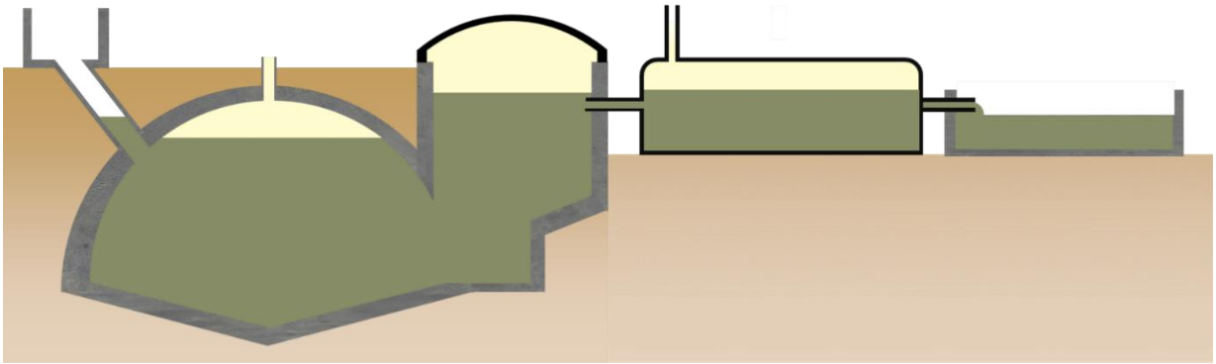

Figure 6-8: Conceptual drawing for the fixed-dome with covered overflow tank and flexi

6.7.3 Option 3: Fixed-dome with covered overflow tank

The third option is shown in Figure 6-9 and consists out of a cover placed over the overflow tank in order to capture the gas released and produced in the overflow tank. Because the overflow tank is covered, a classic manhole is needed when using a rigged cover and a zip-like opening is needed when using a flexible cover. The only extra gas production comes from the overflow tank. This design requires few adjustments and has a low additional cost compared to the fixed-dome digester.

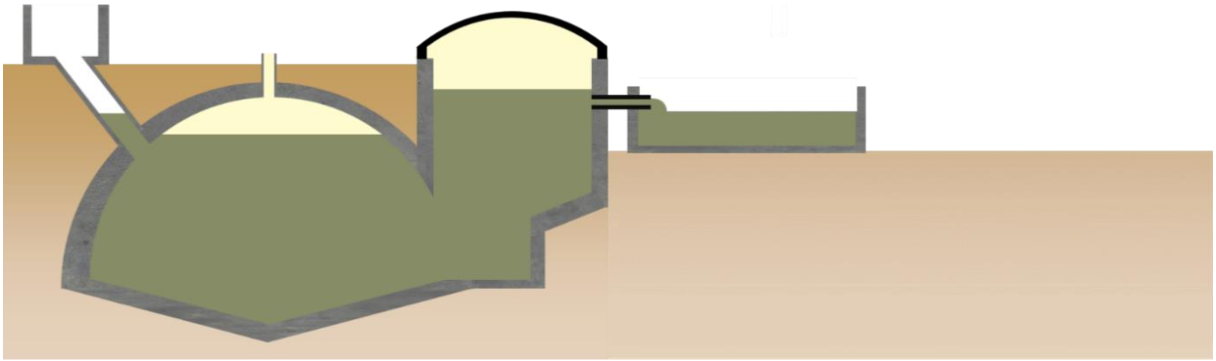

Figure 6-9: Conceptual drawing for the fixed-dome with covered overflow tank

6.7.4 Option 4: Fixed-dome with no overflow tank and with flexi

The fourth option is shown in Figure 6-10 and consists out of a flexi biogas installation that replaces and operates as the overflow tank. The only extra gas production comes from the flexi biogas installation. The performance can be considered approximately the same as option 3 (fixed-dome with covered overflow tank), however, option 4 requires more adjustments to the design of the fixed-dome plant and can be a bit more expensive. The biggest adjustments are firstly the complete redesign of the overflow tank because the flexi biogas installation has to act as the overflow tank and secondly the need for a manhole on top of the fixed-dome digester in order to be able to enter the digester. The addition of a manhole on top of the fixed-dome digester weakens the structure as discussed in section 4.3.2 and therefore may reduce the lifespan of the fixed-dome digester.

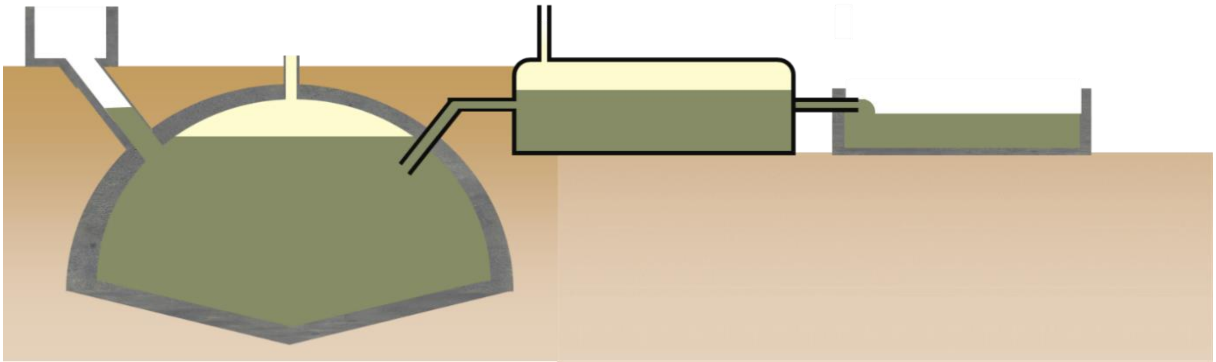

Figure 6-10: Conceptual drawing for the fixed-dome with no overflow tank and with flexi

6.7.5 Choice of hybrid biogas installations

Of the options discussed, option 4 (fixed-dome with no overflow tank and with flexi) requires the most adjustments. While this option has the same additional gas production as option 3 (fixed-dome with covered overflow tank). Option 1 (fixed-dome and flexi) provides for extra gas production in the flexi installation. However, this option does nothing with the large potential of gas production in the overflow tank. For these reasons, options 1 and 4 are not chosen. Options 2 (fixed-dome with covered overflow tank and flexi) and 3 are both good options that require little adjustment. However, option 2 has the highest efficiency, the highest gas production and the most complete digestion process. In other words, option 2 meets the objectives of the hybrid installation the best (increasing the efficiency and eliminating the disadvantages of the fixed-dome installation). Therefore option 2 is chosen.

7 Treatment processes for biogas installations

In this chapter, the treatment processes for biogas installations are discussed. These treatment processes are necessary in order to get the most efficient digestion process possible and to avoid problems with the feeding of the digester. In addition, post-treatment of the digestate is discussed to ensure safe handling of the digestate. The last treatment discussed is the treatment of biogas.

7.1 Pre-treatment of biomass

This section discusses biomass pre-treatment. Biomass that serves as a feedstock for the digester usually requires appropriate pre-treatment. This pre-treatment consists of reducing the particle size and mixing it with water before the biomass is fed to the digester [9].

Various pre-treatment techniques are available. The effect of pre-treatment is highly dependent on the biomass and on the pre-treatment technique. For food waste, a simple mechanical pre-treatment to reduce the particle size is sufficient, such as grinding [37], [38]. Mechanical pre-treatment is a simple technique aimed at increasing the specific surface area of the biomass. In addition to increasing biogas yield, reducing particle size also has an effect on the viscosity. This prevents the formation of floating layers. These floating layers can cause problems in the digester such as blockage of the outlet, these layers may not digest and prevent the escape of the gas [36]. The grinding can be carried out by an electric grinder or a manually operated grinder. The grinders can be classified into 3 types: hammer grinders, knife grinders and grinders that use a combination of both techniques. A grinder that uses knives cuts the fibers and produces small pieces. While a hammer grinder grinds the fibers and usually produces long thin fibers. Both techniques are shown schematically in Figure 7-1 [39].

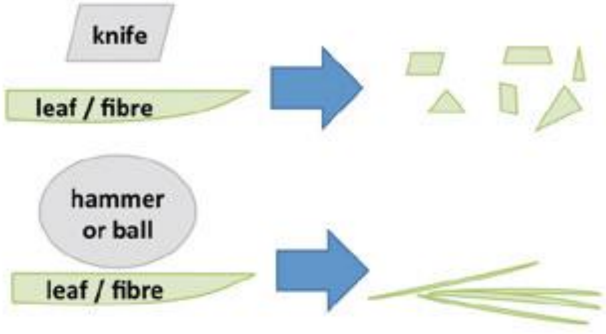

Figure 7-1: Difference between grinding with a knife and a hammer [22]

In the situation for this master's thesis, an electric grinder is opted for. Due to the large amounts of organic waste to be processed, a manual grinder becomes too laborious and will take too much time. The electric shredder chosen uses blades instead of a hammer. This is more efficient and the fibers obtained with the hammer grinder can cause problems in the digester and the inlet pipe.

7.2 Post-treatment and storage of the digestate

Digestate is besides biogas another output product of the biogas installation. Usually, the digestate from a wet digestion installation is very liquid. Therefore, processing and storing the digestate is more complex than for example compost. In rural areas, the digestate can often be used as agricultural fertilizer by local farmers. In urban areas such as Mombasa, this is not always obvious. Transporting the digestate to nearby agricultural fields is not feasible because the digestate is mainly liquid and therefore not easy to transport. The digestate can however be used in nearby parks or gardens. If this is not possible, the digestate can be discharged into the sewer system or directly into the water. If it is discharged directly into the water, the digestate must be treated to prevent water pollution. The digestate from a digester using kitchen waste (which is the case for this project) is safe for reuse in the garden and is a good organic fertilizer [9].

The anaerobic digestion process is very effective in the inactivation of most pathogenic matter such as bacteria, viruses, intestinal parasites, weeds, plant seeds and plant diseases [36]. Despite this inactivation, the digestate coming out of the digester can still contain viruses, bacteria and parasites. The level of digestate hygiene depends on the temperature and retention time in the digester. The higher the temperature and the longer the retention time, the more hygienic the digestate. A mesophilic digester can therefore not ensure the complete removal of these viruses, bacteria and parasites in the digester [9].

The main organisms killed in biogas installations are typhoid fever, paratyphoid, cholera and dysentery bacteria (in one or two weeks), hookworm and schistosomiasis (in three weeks). Tapeworms and roundworms, together with other pathogenic matter can be killed/inactivated by drying the digestate in the sun [23].

As a suitable and simple post-treatment, the digestate can be dried in the sun and then composted. A hygienic product is obtained due to the high temperatures during the composting process [9]. Figure 7-2 shows the relationship between temperature and time needed to inactivate pathogens.

There are also more specified systems for post-treatment of the digestate such as DEWATS (Decentralized Wastewater Treatment Systems), however, these specified systems are rarely used in developing countries [9].

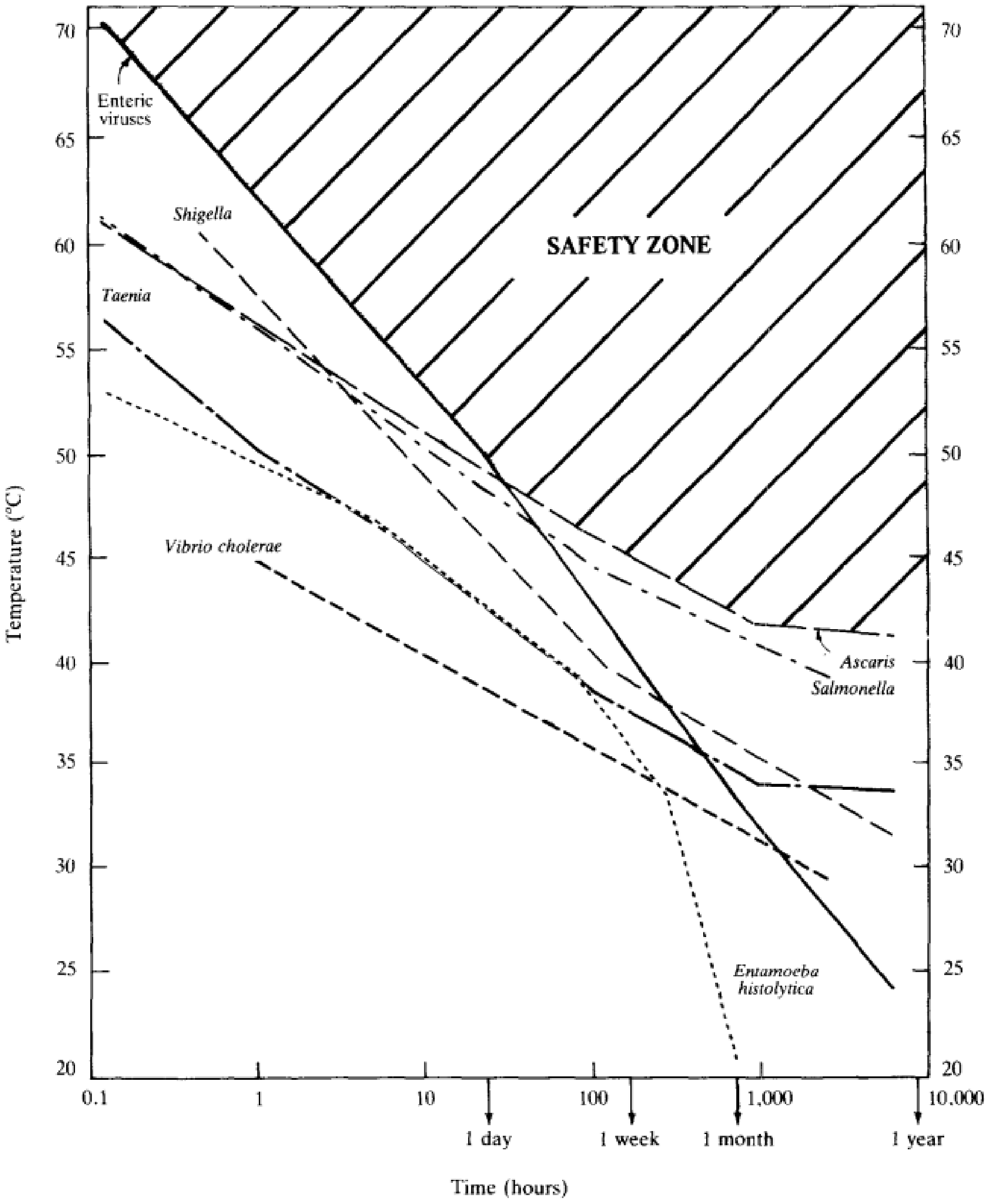

Figure 7-2: Relationship between temperature and time needed to inactivate pathogens [40]

7.3 Post-treatment of biogas

The biogas that leaves the digester contains toxic hydrogen sulfide (H_2S) and is nearly 100% saturated with water vapor. Depending on the application of the biogas, the H_2S and water vapor must be removed [9].

7.3.1 Dewatering

Water vapor can cause various problems. It can cause corrosion and thus damage in the pipework and in the operating equipment (e.g. the gas stove). The accumulated condensed water can also cause blockages in the pipework. The condensed water is formed because the vapor cools down on the pipes and condenses [9]. The condensate always accumulates at the lowest point of the pipeline, the formed water pockets must be avoided [23].

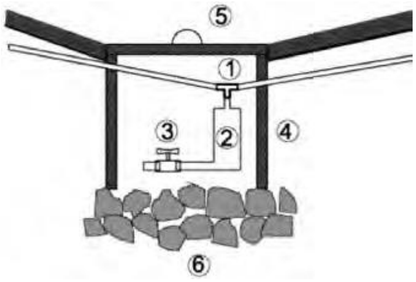

Figure 7-3: Manual water trap [9]

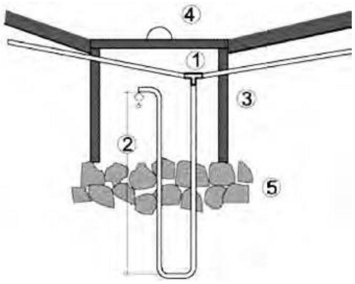

Figure 7-4: U-shaped symmetric water trap [9]

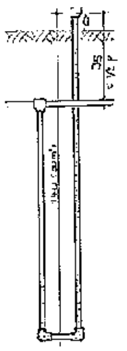

Figure 7-5: U-shaped asymmetric water trap [41]

A condensation separator will be installed at each of the lowest point in the pipeline in order to avoid these problems. The condensation separator can be manual (Figure 7-3) or automatic (Figure 7-4 and Figure 7-5), an automatic operation is desired.

A water trap usually uses a U-pipe and can be symmetric (Figure 7-4) or asymmetric (Figure 7-5). The length of the open water pipe (number 2 in Figure 7-4) should be equal to the maximum gas pressure in the water column + 30% [9]. When using an asymmetric water trap, the maximum length of the pipe above the pipeline is half of the maximum pressure [41].

7.3.2 Desulphurization

Hydrogen sulfide (H_2S) is present in the biogas, hydrogen sulfide itself is a colorless gas with a clearly recognizable rotten egg smell. H_2S is toxic at concentrations greater than 15 ppm. Usually H_2S is smelled before it reaches a toxic concentration. Biogas has an H_2S concentration of 200 to 2,000 ppm. If the biogas is used for cooking and the air-to-gas ratio is correct during combustion, H_2S is burned and directly converted into sulfur. However, incomplete combustion produces sulfur dioxide, which can lead to headaches and breathing problems. Complete desulphurization, however, causes biogas to lose its smell, which is an unpleased warning smell, increasing the risk for an undetected leak. Sulfide is very corrosive and can cause corrosion of the piping and of the gas stove. In order to prevent corrosion of equipment and thus avoid problems with the pipeline and the gas fire, desulphurization will be done. A desulphurator can be purchased off the shelf, this will also be done

7.3.3 Removal of CO_2

CO_2 is present in biogas with a concentration of 35-40%. If CO_2 is removed, the energy density of a unit volume of biogas increases considerably. Despite this, CO_2 is usually not removed in developing countries because CO_2 does not interfere when biogas is used for cooking [9]. CO_2 can be removed from the biogas by passing the gas through water containing an alkaline chemical [9], a water washing system [42], water scrubbing, membrane systems, pressure swing adsorption, chemical CO_2 absorption, amine gas treatment and CO_2 by cooling and recovering dry ice. All these techniques are an additional cost and require a complicated construction or have maintenance costs (such as water scrubbing, which requires regular renewal of steel wool) [43]. Because CO_2 does not interfere with the cooking process, and CO_2 removal would bring additional construction and maintenance costs, CO_2 removal will not be applied for this project.

8 Designing and calculating of the hybrid digester

The hybrid digester consists of a fixed-dome digester with a covered overflow tank and additionally a flexi biogas installation. The last one provides a better efficiency of the digestion process which is taken into account in chapter 9.2. The volume of the digester and has to be adjusted to the available amount of biomass. This volume is one of the factors determining the amount of gas produced. Another factor that determines the volume of the digester is the retention time of the biomass. This relationship is shown in equation (8.1).

$$v = \frac{V_d}{R} \tag{8.1}$$

v: daily feed rate (m^3/day)
V_d: digester volume (m^3)
R: slurry retention time (days)

8.1 Retention Time

There are two types of retention time: the hydraulic retention time (HRT) and the retention time for solids (SRT), but for solid waste digestion these are considered equal. In the manual 'Anaerobic Digestion of Biowaste in Developing Countries' they are defined as follows:

> Hydraulic Retention Time (HRT): Defines the (average) amount of time that liquid and soluble compounds stay in a reactor. It has the unit of time and is calculated by dividing the volume of the reactor by the flow.
>
> Solids Retention Time (SRT): The average length of time solid material remains in a reactor. SRT and HRT are equal for complete mix and plug flow reactors. Some two-stage reactor concepts decouple HRT from the SRT allowing the solids to have longer contact time with microbes while maintaining smaller reactor volume and higher throughput [9, pp. 6-7].

In general, the retention time R is considered to be the time that the slurry requires to stay in the digester pit for complete digestion by bacteria. For continuous digester systems, the daily feed rate (v) is arrived at by dividing the digester volume (V_d) with the slurry retention time (R) [44].

The microorganisms need enough retention time to convert organic materials into biogas. The retention time required to enable full anaerobic digestion reactions depends on the technology that is used. Other factors that influence this are the process temperature and the composition of the bio-waste. Recommended HRT for waste processed in a mesophilic digester varies from 10 to 40 days. Retention time is the most important factor that determines biogas production. It determines on the one hand the quantity and on the other hand the speed of the methane yield. A higher retention time leads to a higher volatile solids reduction and a higher required digester volume (V_d). A shorter retention time, however, leads to a lower required digester volume (V_d) and therefore lower investment costs. The retention time also affects the concentration of microorganisms in digesters that are not equiped with systems designed to maintain or recycle microbial biomass. A minimum retention time of 10 to 15 days is therefore required in such digesters to prevent the leaching of biomass [9], [38].

The retention time also affects how hygienic the digestate is. The longer the digestion time, the more fully the biomass is digested and therefore more pathogens are killed which results in a more hygienic digestate [23].

8.1.1 Determining the retention time

The ideal retention time for a tropical climate with an average ambient temperature of 25–30 °C is recommended to be around 30 days [9], [19]. In this climate, the digester operates at mesophilic temperature (without external heating). Figure 8-1 shows the cumulative biogas production (for a mesophilic temperature) from the first-order kinetic model and from an experimental setup and the effect of total solids in function of the retention time [45]. In this figure, we can see that biogas production does not increase much from day 25, so a good retention time according to this model is 25 days. The experimental setup however is an anaerobic batch digester with a total volume of 2 l, while the fixed-dome digester is a continues operated digester. In practice, such an experiment cannot be done with a continuously or semi-continuously operated digester for a number of reasons [36]. The retention time according to the model (25 days) and the recommended retention time (30 days) are close to each other. Because the model is for a batch-operated digester and therefore the result may differ from a continuous digester, a retention time of 30 days is chosen.

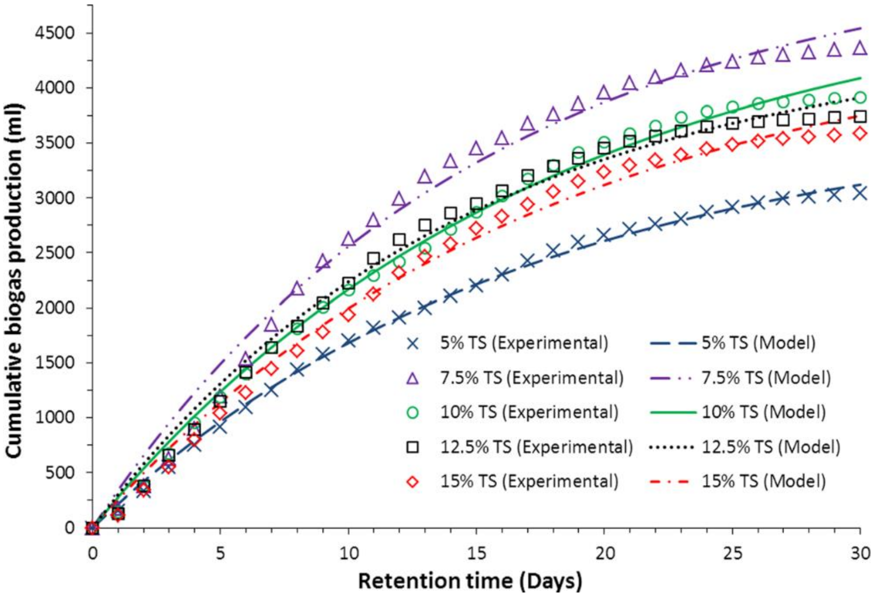

Figure 8-1: Cumulative biogas production from the first-order kinetic model and from an experimental setup and the effect of total solids [45]

8.2 Substrate input

Before biomass is added to the digester, it must be diluted with water. Diluting biowaste with water helps to control the total solids fed to the digester. Feeding too much TS can lead to clogging of the pipes. Too little TS (i.e., too much dilution with water) will reduce the potential gas yield. The amount of water to be added depends on the feed material and more specifically the volatile solids. The most commonly used feed materials are manure and food waste. Manure is more aqueous than food waste so less water needs to be added. The TS values suggest a manure to water ratio of just under 1:1 for cow manure and 1:2 for pig manure. For food waste a ratio of 1:2 to 1:3 is used [9], [46], [47]. The exact mixing ratio is determined in chapter 8.3.2. The total daily quantity is then determined in (8.2).

$$v = B + W$$
$$v = B + \frac{B}{x} \tag{8.2}$$

v: total daily feed rate (m^3/day)
B: daily biomass feed rate (m^3/day)
W: daily water feed rate (m^3/day)
x: biomass/water ratio

The volume of the digester is calculated based on a biomass/water ratio calculated in section 8.3.2. If the added amount of water is less than the recommended amount based on the biomass/water ratio, the retention time will increase for the same digester volume.

8.3 Calculating of the fixed-dome digester

This section discusses the design and calculating of the digester. At the end of this section, the digester is dimensioned.

8.3.1 Background conditions

The background conditions follow from prior research:

> Technical University of Mombasa is a public higher learning institution located in the coastal city of Mombasa, Kenya, Tudor location, along Tom Mboya avenue. It has over 10,000 students learning in its different schools and Institutes, and over 1,000 members of staff. It has 4 cafeterias within the main campus and The Kiziwi hospitality and conference center cafeteria at the Kiziwi Campus. These cafeterias serve over 4,000 students, over 500 staff members and over 200 outsiders on a daily basis [48, p. 2].

8.3.2 Calculating the water/biomass ratio

It is stated in prior research that “The campus and its environs cafeterias generates over 300 kg of waste daily, 60% of which is food waste (= 180 Kg) [48, p. 2]”. However, this number is on the higher side, the actual amount of food waste varies between 75 and 200 kg a day with an average of 100 kg per day. The digester will be sized for 100 kg of food waste per day.

The available biowaste (mix of vegetable, fruit and food waste) has a Total Solids (TS) or dry matter content of 10% on average [36]. In other words of the 100 kg wet weight, 10%, which is equal to 10 kg, is dry matter.

“For sufficient biogas production, the input must contain 7–9% dry matter” [49, p. 5]. In this range of 7-9%, biogas production can still differ. The effect of the percentage of total solids (TS) on biogas production is shown in Figure 8-1. According to this figure, biogas production is maximized at a TS of 7.5%. The required amount of water is calculated for 7.5% and 9% total solids.

For 9% total solids

This 10 kg then corresponds to 9% dry matter. This must be diluted with 91% water.

$$\frac{10\ kg}{9\%} \cdot 91\% = 101.1\ kg\ water \tag{8.3}$$

Biomass/water ratio:

$$x = \frac{B}{W} = \frac{100}{101.1} = 0.989 \approx 1:1 \tag{8.4}$$

For 7.5% total solids

This 10 kg then corresponds to 7.5% dry matter. This must be diluted with 92.5% water.

$$\frac{10\ kg}{7.5\%} \cdot 92.5\% = 123.3\ kg\ water \tag{8.5}$$

Biomass/water ratio:

$$x = \frac{B}{W} = \frac{100}{123.3} = 0.81 \ \approx 1:1.25 \tag{8.6}$$

It is better to oversize the digester rather than undersize it. By over dimensioning the digester, higher production is achieved because the retention time increases and in this way the digester is also future proof for when in the future more food waste becomes available. In practice, the exact amount of water added to the food waste will not be measured, but there will be looked at the texture and liquid character of the waste-water mixture. The mixture must be sufficiently watery to prevent clogging and to ensure a smooth flow. Therefore, a water ratio of about 1:3 is usually applicable [9], [46], [47]. Because of this, a biomass/water ratio of 1:3 is chosen. So approximately 300 liters of water needs to be added to the food waste every day. However, this ratio is more than the optimal theoretically achieved ratio of 1:1.25. This ratio depends on parameters such as %TS, which can vary between 9-37% [9]. Due to this variation, the result that follows from practical experience is more reliable than the theoretical result.

8.3.3 Daily biowaste production

The available biowaste consists of kitchen and canteen waste (such as vegetable and fruit peelings and food leftovers). This raw feedstock will be diluted with water in a ratio of 1 part waste to 3 parts water as mentioned before. This will result in a slurry that can be easily flushed into the digester. The daily total quantity of diluted feedstock (v) is calculated with equation (8.2)[3].

$$v = 100 + 3 \cdot 100$$
$$v = 300\ l/day\ = 0.4\ m^3/day$$

---

[3] Using the approximation that 1 kg substrate is equivalent to 1 l [9].

8.3.4 Retention Time (R)

The ideal retention time for a tropical climate with an average ambient temperature of 25–30 °C is recommended to be around 30 days [9]. The active reactor volume follows from equation (8.1).

$$V_d = v \cdot R$$
$$V_d = 0.4 \cdot 30$$
$$V_d = 1200\ l = 12\ m^3$$

To get an idea of the size of the fixed-dome digester, the radius is calculated with equation (8.7) from a hemisphere with a volume of 12 m³.

$$V = \frac{2}{3} \cdot \pi \cdot r^3 \tag{8.7}$$
$$r = \sqrt[3]{\frac{V \cdot 3}{\pi \cdot 2}}$$
$$r = \sqrt[3]{\frac{12 \cdot 3}{\pi \cdot 2}}$$
$$r = 1.79\ m$$

V: volume of a hemisphere (m³)
r: radius of the hemisphere (m)

The volume of the digester does not only consist of a hemisphere but also an upside-down cone-shaped bottom, an inlet and an outlet. Especially the bottom and the outlet have an extra influence on the volume of the digester, the effect of the inlet is neglected.

8.3.5 Calculating the dimension

The digester is dimensioned based on the available biomass, the desired retention time and the required amount of water addition. However, the design and construction of the overflow tank should also be well done.

The bottom of the overflow tank must correspond to the zero-fill line, this is shown in Figure 8-2. If the bottom of the overflow tank is too low, some parts of the slurry will be exposed to the air, affecting the digestion process and some gas may escape, if it is too high, the slurry level will rise and the digester will be completely full, blocking the gas outlet. The shape of the overflow tank is very critical because it determines the height of the slurry surface [20]. Because the parameter h is always smaller than the parameter H, the digester will never be completely full.

The main dimensional parameters are shown in Figure 8-2. The meaning of these parameters is shown in Table 8-1.

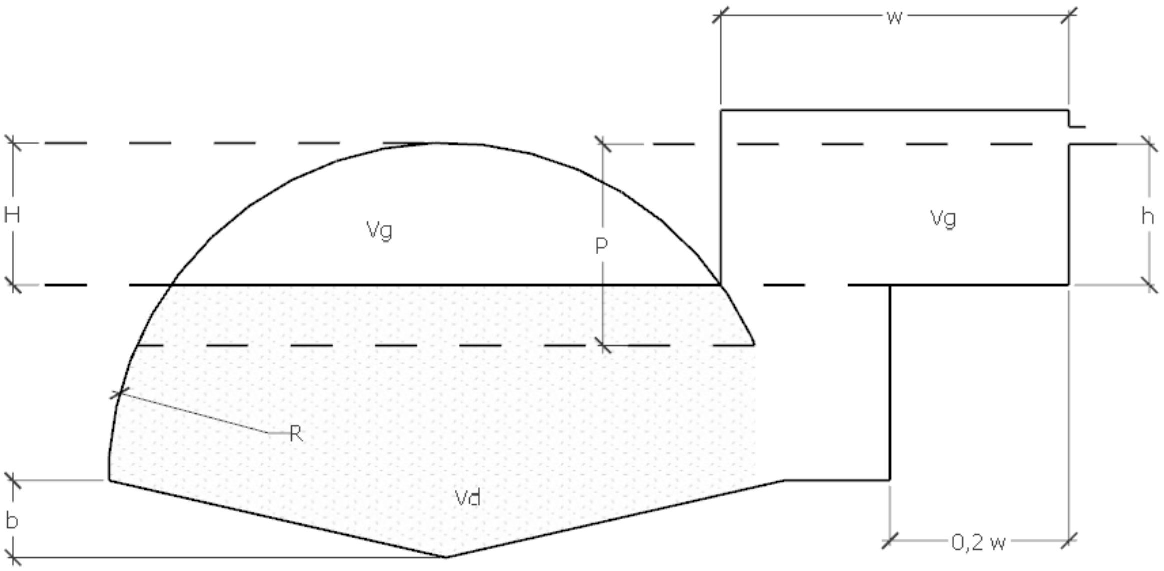

Figure 8-2: Dimensional parameters of the chosen model [20]

Table 8-1: Meaning of the main dimensional parameters [20, p. 165]

V_D	Required digester volume	V_g	Required gasholder volume
H	Depth of the gasholder	h	Height of the overflow chamber
b	Depth of the digester base	w	Length of the overflow chamber
p	Height corresponding to the maximum gas pressure	R	Radius of the digester

In order to size the digester, a digester/gasholder ratio must be chosen (the gasholder in this ratio refers to the volume of the gasholder present in the digester). If an external gasholder would not be used, gas production and consumption would first need to be calculated, from which the volume of gas storage would follow and thus the digester/gasholder ratio would be fixed. However the chosen design uses an external gasholder, therefore the volume of the gasholder in the digester can be chosen freely. For this volume, gas production should not be taken into account, the volume provides a little margin, if more biomass will be supplied. A small digester/gasholder ratio of 1:8 is chosen because there is no need for large internal gas storage.

$$V_G = \frac{V_D}{8} = \frac{12}{8} = 1.5\ m^3 \tag{8.8}$$

Table 8-2 shows the relationship between the main dimensional parameters for various digester/gasholder ratios.

Table 8-2: Relationships between the digester parameters for various ratio's [23, p. 51]

V_g:V_d	1:5	1:6	**1:8**
R	$\sqrt[3]{0.48\,V_D}$	$\sqrt[3]{0.48\,V_D}$	$\sqrt[3]{\mathbf{0.46}\,\boldsymbol{V_D}}$
H	$0.37R$	$0.35R$	$\mathbf{0.32}\boldsymbol{R}$
h	$0.32R$	$0.30R$	$\mathbf{0.28}\boldsymbol{R}$
P	$0.51R$	$0.47R$	$\mathbf{0.41}\boldsymbol{R}$
b	$0.25R$	$0.25R$	$\mathbf{0.25}\boldsymbol{R}$

First of all, the radius of the digester is calculated for a ratio of 1:8.

$$R = \sqrt[3]{0.46\,V_D} = \sqrt[3]{0.46 \cdot 12} = \;1.77\,m \approx 1.8\,m \tag{8.9}$$

A radius for the digester of 1.6 m is chosen. This radius is used to calculate other parameters using the formulas shown in Table 8-2.

$$\begin{aligned} H &= 0.32R = 0.32 \cdot 1.8 = 0.58\,m \\ h &= 0.28R = 0.28 \cdot 1.8 = 0.50\,m \\ p &= 0.41R = 0.41 \cdot 1.8 = 0.74\,m \\ b &= 0.25R = 0.25 \cdot 1.8 = 0.45\,m \end{aligned}$$

To determine the length and the width of the overflow chamber, the following formula can be used [20]:

$$V_G = l \cdot w \cdot h \tag{8.10}$$

l:	length of the overflow chamber (m)
w:	with of the overflow chamber (m)
h:	height of the overflow chamber (m)

The w: l ratio can be chosen freely, this ratio does not affect the operation of the plant. A w: l ratio of 5:8 is chosen, this ratio is a common ratio for plants in Ghana [20].

$$V_G = l \cdot w \cdot h = \left(\frac{8}{5}w\right) h \cdot w \Rightarrow w = \sqrt{\frac{5\,V_G}{8\;h}} = \sqrt{\frac{5\;1.5}{8\;0.5}} = 1.37\,m \tag{8.11}$$
$$l = \frac{8}{5}w = \frac{8}{5}1.25 = 2.19\,m$$

In order to show the influence of the available biomass on the dimensions and other parameters, the different parameters are also calculated. The calculations are done for the minimum available biomass (75 kg) to the maximum available biomass (200 kg) with increments of 25 kg, the results are shown in Table 8-3.

Table 8-3: Various parameters for 75–200 kg available food waste a day

m	75	100	125	150	175	200
V_{water}	225	**300**	375	450	525	600
v	0.3	**0.4**	0.5	0.6	0.7	0.8
V_d	9	**12**	15	18	21	24
Vg	1.125	**1.5**	1.875	2.25	2.625	3
w/l	0.625	**0.625**	0.625	0.625	0.625	0.625
R	1.60	**1.80**	1.90	20	2.10	2.20
H	0.51	**0.58**	0.61	0.64	0.67	0.70
h	0.45	**0.50**	0.53	0.56	0.59	0.62
p	0.66	**0.74**	0.78	0.82	0.86	0.90
w	1.25	**1.37**	1.49	1.58	1.67	1.74
l	2.00	**2.19**	2.38	2.53	2.67	2.78
b	0.40	**0.45**	0.48	0.50	0.53	0.55

8.3.6 Review of the pressures

In Table 8-2 the parameter ‘p’ is listed as the height corresponding to the maximum gas pressure. In this section, the parameter ‘p’ is represented by h_p to avoid confusion with the symbol for pressure. If the maximum pressure is exceeded, the slurry level will drop below the opening of the overflow tank, resulting in biogas leaking out of the digester through the digester outlet and the slurry/biomass in the digester will be exposed to air, affecting the digesting process. The pressure corresponding to this distance can be calculated using the approximation that 1 kg substrate is equivalent to 1 liter [9] or in other words, the density of the substrate is 1,000 kg/m^3.

$$\begin{gathered} p = \rho g h_p = 1{,}000 \cdot 9.81 \cdot 0.74 = 7259.4\ Pa \\ p_{0.20} = (1 - 0.2)p = 5807.5\ Pa \end{gathered} \tag{8.12}$$

p: gas pressure in the digester (Pa)
ρ: density of the substrate (kg/m^3)
h_p: height corresponding to the maximum gas pressure (m)
g: gravitational acceleration (m/s^2)

A safety margin of 20% is taken into account, so the pressure in the gasholder must remain below 5807.5 Pa. The gas pressure needed for cooking on biogas is much lower than this pressure. The gas pressure required for cooking on biogas is 500–2,000 Pa [23], which is significantly lower than maximum gas pressure. This pressure depends on the design of the stove and the required amount of gas per hour. For example, the paper ‘Design and performance evaluation of biogas stove for community cooking application’ discusses a biogas stove that requires a pressure of 747 Pa and consumes 1,000 liter biogas per hour [50], while the manual 'Anaerobic Digestion of Biowaste in Developing Countries' discusses a biogas stove that requires a pressure of 200/400 Pa and consumes 300/500 l/h [9]. However, pressure losses occur in the pipes, which makes the pressure in gas storage higher than the gas pressure needed for cooking. Because of these pressure losses, the pressure in the digester is equal to the pressure in the external gas reservoir plus the pressure losses in the pipe between the digester and the gas reservoir.

It can be calculated how much the slurry in the digester is removed from the top of the digester (represented by “x”) at a given pressure. This is calculated for a pressure of 500 and 2,000 Pa.

$$x = \frac{p}{g\rho} + H - h \tag{8.13}$$

$$x = \frac{500}{1{,}000 \cdot 9.81} + 0.58 - 0.50 = 13.1\ cm$$

$$x = \frac{2{,}000}{1{,}000 \cdot 9.81} + 0.58 - 0.50 = 28.4\ cm$$

For these pressures and the corresponding levels, we can calculate the actual active reactor volume V_d. This volume can be calculated using simple geometric formulas.

$$V_d = \frac{\pi R^2 b}{3} + \frac{2}{3}\pi R^3 - \pi x^2\left(R - \frac{x}{3}\right) = \frac{\pi \cdot 1.8^2 \cdot 0.45}{3} + \frac{2}{3}\pi \cdot 1.8^3 - \pi x^2\left(1.8 - \frac{x}{3}\right) \tag{8.14}$$

De result of this equation (8.14) for different values of x is shown in Table 8-4.

Table 8-4: Active reactor volume for different values of x and the corresponding pressure

p	294	589	883	1177	1472	1766
x	0.11	0.14	0.17	0.20	0.23	0.26
V_d	13.67	13.63	13.58	13.52	13.45	13.38

Because there will be cooking for a large number of students per day, the cooking pressure will probably be around 1,000 Pa. However, the actual cooking pressure required is also strongly dependent on the biogas stove used. The actual active reactor volume V_d will be around 13.5 m³. However, this volume is only an estimation because the actual gas pressure is not yet known and because the opening of the overflow tank also has a small effect on V_d. The effect of a 1.5m³ larger V_d (in comparison with the designed 12 m³ fixed-dome digester) is rather small, the main effect is that the retention time is about 33.75 days instead of 30 days, this can only have a positive effect on the gas production. In further calculations, V_d = 12 m³ is still used, due to the small effect of a 1.5m³ larger V_d.

8.4 Materials for the construction of the digester

The digester itself can be made from two possible materials: bricks or reinforced concrete/ferro cement. There is not one option that is better than the other. If bricks are used a scaffolding may be needed and if concrete is used a kind of iron framework is needed. It is important that the bricks and cement or concrete used are of good quality in order to prevent cracking and thus gas leaks in the future.

If bricks are used, the lower part of the digester can be plastered. In this way the brickwork is protected against roots that can grow against the digester. Smooth plastering also reduces friction between the digester and the soil and thus also reduces static stress of the brickwork. The lower part of the digester can also be plastered on the inside as an extra waterproof layer [41].

One of the most important things that need to be done is to make digester gas-tight, both for bricks and for concrete. This can be done in different ways. It is particularly important that the upper part of the digester containing gas is gastight. The first option is to paint the digester with gastight paint, it is important that this gastight paint is elastic in order to bridge the cracks in the structure [23]. If the digester is partly above ground, it is best to paint the digester black, because a dark color absorbs the light better and thus the digester can be kept at a higher temperature with the help of sunlight. Another option is to add a water-proofer to the cement or concrete for gas tightness. It is preferred to use plastic-based water-proofer over crystalline components because of greater elasticity. In order to obtain gas tightness, it is best to add twice the amount recommended by the manufacturer for water-tightness [41].

9 Calculation of the gas production, consumption and sizing of the gasholder

This section discusses the calculations in order to estimate the biogas production, the design and dimensioning of the gasholder. A simulation will be done based on the consumption pattern and the expected production to determine the peak gas content of the gasholder. The size of the gasholder will be based on the results of the simulation. The volume of the gasholder depends on four parameters: the daily gas production, the time when the tap from the digester to the gasholder is opened, the amount and time when biogas is used.

9.1 Estimation of biogas production of the fixed-dome digester

The daily gas production depends on numerous factors, such as the type and amount of feed material, the digestion temperature, the retention time. These factors are discussed earlier.

An average of 100 kg of food waste per day is available, this is discussed in section 8.3.2. As mentioned earlier the available feedstock has a total solids content (TS) of 10% on average [36]. This means that of the 100 kg wet weight, 10 kg is dry matter. Of this 10 kg dry matter, 80% is volatile [36]. So the amount of the volatile solids is 8 kg and the non-volatile amount is 2 kg. The rest of the biowaste is water and does not contains volatile solids. So it can be concluded that of the 400 kg of feedstock (100 kg food waste + 300 kg water) the volatile solids (VS) is 8 kg. Using the approximation that 1 kg substrate is equivalent to 1 liter, 1,000 liters of biomass (food waste + water) would contain 20 kg volatile solids (20 kg VS /m^3) [9].

First, the organic load rate (OLR) is calculated in equation (9.1). The OLR is one of the most important parameters affecting the biogas production and microbial populations during anaerobic digestion. OLR is the Amount of organic material fed daily to a digester. More precisely, OLR is the amount of VS fed per volume of a digester per day and expressed in kg VS/m^{3}day.

$$OLR = Q \cdot \frac{S}{V_D} = 0.4 \frac{m^3}{day} \cdot \frac{20\ \frac{kg\ VS}{m^3}}{12\ m^3} = 0.67 \frac{kg\ VS}{m^3\ reactor \cdot day} \tag{9.1}$$

OLR: organic load rate ($kg\ VS/m^3\ reactor \cdot day$)
Q: substrate flow rate (m^3/day)
S: substrate concentration in the inflow (kg VS /m^3)
V_D: active reactor volume (m^3)

The organic load rate of the digester is 0.67 kg VS/m^{3}day and for a non-stirred biogas installation an OLR below 2 kg VS/m^{3}day is considered ideal [9].

The biogas yield mainly determines the biogas production per day. Therefore, as a next step, the biogas yield is verified. In the calculations, the assumption will be made that biogas consists for 65% out of methane [9], [51], [52]. Using a first-order kinetic model, methane production can be calculated. The methane and biogas production for food waste is given by equation (9.2) [36]. In order to get the biogas and methane production, the retention time must be given as the time in equation (9.2).

$$Y(t)_{methane} = Y_{max}[1 - 0.88 \cdot e^{1.02 \cdot t} - (1 - 0.88)e^{-0.06 \cdot t}]$$
$$Y(30\ days)_{methane} = 0.46 \frac{m^3 CH_4}{kg\ VS} \tag{9.2}$$
$$Y(30\ days)_{biogas} = \frac{Y(30\ days)_{methane}}{65\%} = 0.71 \frac{m^3 biogas}{kg\ VS}$$

$Y_{methane}$: methane yield ($m^3 CH_4 / kg\ VS$)

Y_{biogas}: biogas yield ($m^3 biogas / kg\ VS$)

t: time (days)

Table 9-1 summarizes the biogas yield. The average value of 0.66 $\frac{m^3 biogas}{kg\ VS}$ is used.

Table 9-1: Biogas yield from different sources

Biogas yield $\left(\frac{m^3 biogas}{kg\ VS}\right)$	**Source**
0.71	equation (9.2) [36]
0.61	[9]
0.66	Average

The next step is to calculate the biogas production from the fixed-dome installation. Table 9-1 shows the average biogas yield for food waste with the assumption of a methane (CH_4) content of 65% (see section 9.1). The daily biogas production can be calculated with equation (9.3) [9]:

$$Q_{biogas} = Y_b \cdot VS = 0.66 \frac{\mathrm{m}^3}{\mathrm{kg}} \cdot 8 \frac{kg}{day} = 5.28 \frac{m^3}{\mathrm{day}} \tag{9.3}$$

Q_{biogas}: Biogas production per day (m³/day)
Y_b: biogas yield (m³/ kg VS)
VS: volatile solids per day (kg/day)

So it can be concluded that approximately 5.28 m³ biogas is produced per day or 220 liters per hour in the fixed-dome digester. Gas production during day and night is virtually the same [23].
Next, the gas production rate (GPR) is calculated with equation (9.4).

$$GRP = \frac{Q_{biogas}}{V_D} = \frac{5.28}{12} = 0.44\ m^3 \text{ biogas } / m^3 \text{ reactor and day} \tag{9.4}$$

The Specific Gas Production (SGP) can be calculated with equation (9.5).

$$SGP = \frac{GRP}{OLR} = \frac{0.44}{0.67} = 0.65\ m^3 \text{ biogas } / \ kg \text{ VS fed material} \tag{9.5}$$

9.2 Estimation of biogas production of the hybrid installation

In section 6.4 the results of a similar hybrid system are discussed. This test installation shows that an equal gas flow as in the fixed-dome installation was obtained from the overflow tank. However, there is no literature to back this up. The assumption that a covered overflow tank can double the output of the fixed-dome plant is optimistic. Because a lot of fresh biomass will occur in the overflow tank, the overflow tank has a lot of potential for extra gas production. An added gas production of 75% obtained from the covered overflow tank is assumed.

The output of the overflow tank is already partially digested. Therefore, the input for the flexi installation has a lower potential for gas production than the food waste. Because of this, a gas production equal to 50% of the gas production of the fixed-dome installation is assumed. In total, gas production is assumed to be 2.25 times that of the fixed dome plant, giving $Q = 11.88\ \mathrm{m^3/day}$.

9.3 Simulations of the production and the consumption

In order to determine the volume of the gas container, the gas consumption must be known and the times of gas consumption. However, there needs to be noted that on Saturday, the daily gas consumption is just 20% of the gas consumption during the weekdays and on Sunday only 10%. This must be taken into account when determining the volume of gas storage. Existing installations show that 40-60% of the daily biogas production has to be stored [11], [23]. According to these estimations, the volume of the gasholder should approximately be 4.8-7.1 m^3. However, the needed amount can differ a lot from these values depending on the consumption pattern.

As mentioned, the scullery will be provided with biogas. The scullery uses firewood and charcoal. A good idea of the consumption pattern is needed in order to get a good result for the required size of the gasholder. However, some estimations are needed. Due to the Covid-19 pandemic, the occupancy of the kitchen is about 1/3 compared to the normal situation. The first assumption made is that normal energy consumption is three times higher than in the calculated consumption (based on data collected during the Covid-19 pandemic).

9.3.1 Determining biogas equivalent of the firewood and charcoal

In order to calculate the biogas equivalent of the firewood and charcoal, the calorific value of the firewood, the charcoal and the biogas and the efficiency of the firewood, charcoal and biogas stove has to be known. The biogas equivalent of 1 kg of firewood and charcoal will be calculated.

The net calorific value of firewood (log wood) is 14.7 MJ/kg [53], the net calorific value of charcoal is 28.4 MJ/kg [54] and the net calorific value of biogas is 23.27 MJ/m^3 with the assumption that the biogas consists of 65% methane (calorific value of methane is 35.8 MJ/m^3) [54]. To convert the consumption to biogas, the efficiency of the different stoves is needed. The stove for the firewood that is used is relatively similar to a CISIR'S single pot stove, this stove has an efficiency of 24% [55]. A biogas stove has an efficiency of 55% and a charcoal stove 30% [56]. The firewood and charcoal biogas equivalent is calculated in equations (9.6) and (9.7).

$$V_{firewood} = NCV_{firewood} \cdot \frac{\eta_{firewood}}{\eta_{biogas} \cdot NCV_{biogas}} = 14.7 \cdot \frac{0.24}{0.55 \cdot 23.27} = 0.276 \frac{m^3}{kg\ firewood} \tag{9.6}$$

$V_{firewood}$: biogas firewood equivalent ($m^3/kg\ firewood$)
$NCV_{firewood}$: net calorific value of firewood (MJ/kg)
NCV_{biogas}: net calorific value of biogas (MJ/kg)
$\eta_{firewood}$: efficiency of the firewood stove (%)
η_{biogas}: efficiency of the biogas stove (%)

$$V = NCV_{charcoal} \cdot \frac{\eta_{charcoal}}{\eta_{biogas} \cdot NCV_{biogas}} = 28.4 \cdot \frac{0.30}{0.55 \cdot 23.27} = 0.666 \frac{m^3}{kg\ charcoal} \tag{9.7}$$

$V_{charcoal}$: biogas firewood equivalent $\left(\frac{m^3}{kg\ firewood}\right)$
$NCV_{charcoal}$: net calorific value of charcoal (MJ/kg)
$\eta_{charcoal}$: efficiency of the charcoal stove (%)

The calculations conclude that 1 kg of firewood is equivalent to 0.276 m³ of biogas or 1 m³ of biogas is equivalent to 3.63 kg of firewood and 1kg of charcoal is equivalent to 0.666 m³ of biogas or 1 m³ of biogas is equivalent to 1.50 kg of charcoal.

9.3.2 Consumption pattern

The consumption pattern that will be discussed is during the Covid-19 pandemic. The current consumption is estimated 3 times lower than in the normal situation (after Covid-19) as mentioned earlier. An overview of the consumption pattern is shown in Table 9-2. However, there needs to be noted that on Saturday, the daily gas consumption is just 20% of the gas consumption during the weekdays and on Sunday only 10%. This must be taken into account when determining the volume of gas storage.

Table 9-2: Overview of the consumption pattern of a weekday

Start hour cooking period	End hour cooking period	kg firewood	kg charcoal	Food
03:15	05:45	22.5		beans
08:00	08:30	6.5		rice
10:00	11:00	7.2	7.0	pilau and ugali
11:00	12:00		3.5	chips
12:30	13:30		3.8	chips

As mentioned in section 1.3, the kitchen will also be provided with hot water, by another project. Because of this, the water should not be boiled starting from room temperature, but from an average of 45°C. This means that less biogas is required. An overview of the consumption is shown in Table 9-3.

Table 9-3: Consumption overview of a week day in non-Covid-19 period

Duration	Firewood [kg]	Charcoal [kg]	Biogas equivalent [m³]	Water temp. [°C]
2:30	67.5	0.0	18.63	47
0:30	19.5	0.0	5.38	46
1:00	21.6	21.0	19.95	45
1:00	0.0	10.5	6.99	45
1:00	0.0	11.4	7.59	44

The biogas equivalent is calculated using the values obtained with equations (9.6) and (9.7). The biogas equivalent does not include the biogas savings from the preheated water.

When looking at the total consumption (taking into account that there is less consumption at the weekend), a biogas equivalent of ± 310 m³ biogas is consumed over a whole week, while ± 83 m³ biogas is produced over a whole week. From this, it can be concluded that about 27% of the energy demand of the scullery can be covered with biogas.

9.3.3 Gas tap regulation

In a standard fixed-dome digester, fresh biomass regularly enters the overflow tank. This happens when fresh biomass is brought into the digester, which will also be the case with the hybrid installation with an external gasholder. Each time when gas is consumed or produced, the gas pressure in the fixed-dome digester changes, causing slurry to flow into or out of the overflow tank. This movement of the slurry prevents the formation of a scum layer. A scum layer can hinder gas production. Because an external gasholder is used that guarantees a constant gas pressure in the digester, this constant movement of the slurry due to the changing gas pressure does not take place. For this reason, it is necessary that the pipeline from the fixed-dome digester to the external gasholder is closed at certain times. In this way, there is a movement of the slurry at the times when the tap is closed and when the tap is opened. When closing or opening the tap, the pressure in the digester will suddenly drop to the pressure of the external gasholder (plus pressure losses in the pipe), causing a sudden movement of the slurry. In this way, the formation of a scum layer is prevented.

The easiest way is to open the tap during cooking hours and close it when there is not cooked on biogas. In this way, the tap can be opened when cooking is started and closed when it is stopped. This means the tap is opened at 3:15 and closed at 13:30. This means the tap is opened for approximately 10 hours and closed for 14 hours. When the tap is opened at 3:15, all the gas production from the time when the tap is closed will flow to the gasholder. This results in a maximum gas content in the gasholder.

9.3.4 Results of the simulation

The simulation is done in Python. Appendix A shows the python code of the simulation. The gas content for the gasholder in function of time for 2 weeks and 2 days are chronologically shown in Figure 9-1 and Figure 9-2.

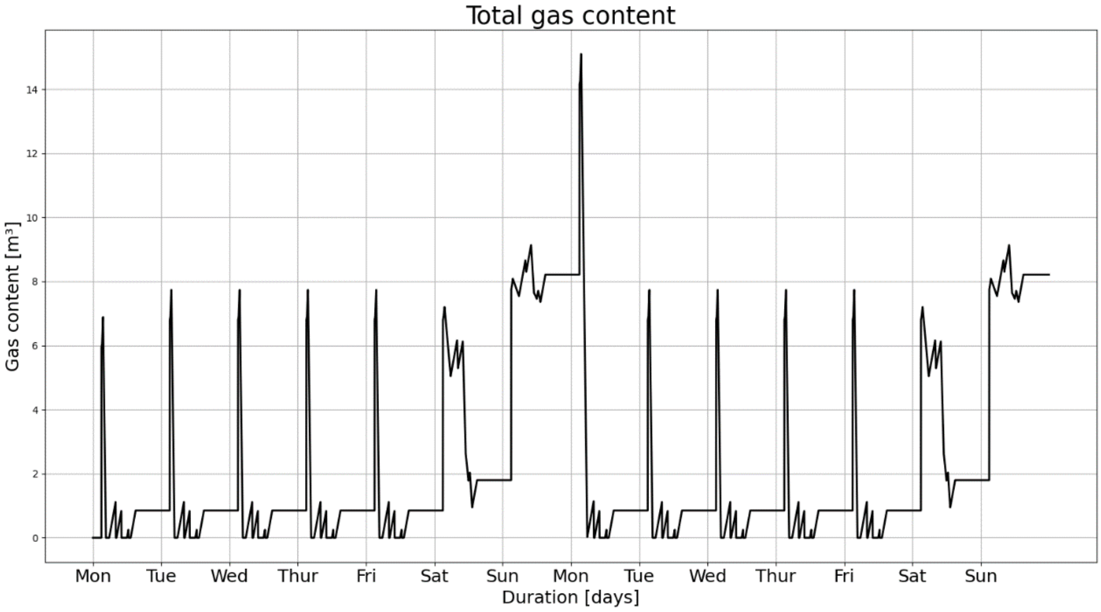

Figure 9-1: Gas content of the gasholder(s) in function of time for 2 weeks

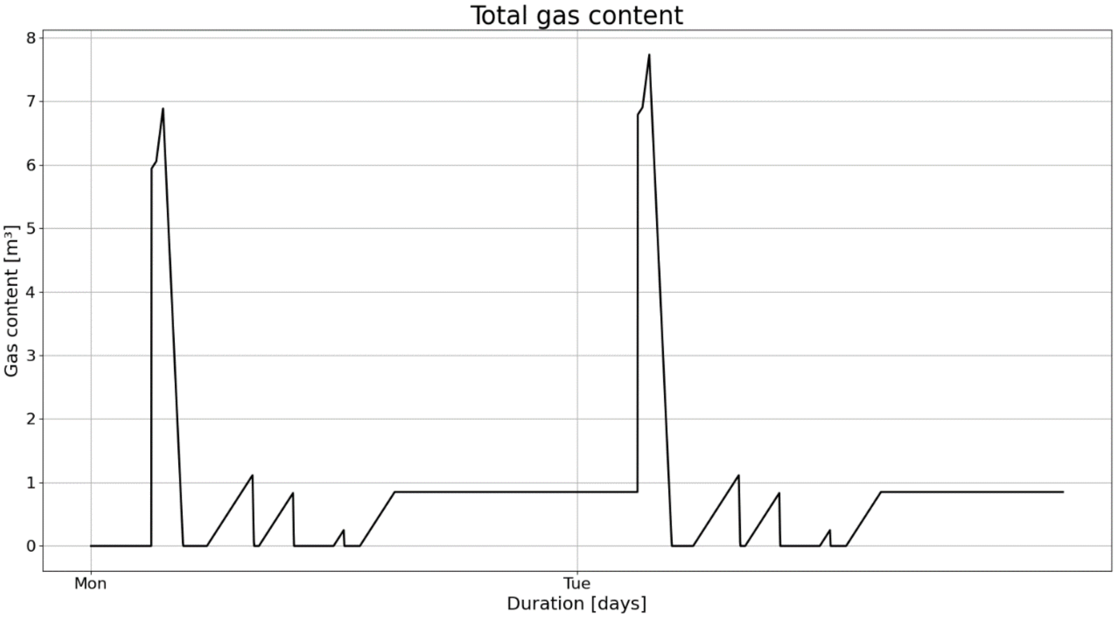

Figure 9-2: Gas content of the gasholder(s) in function of time for 2 weekdays

Figure 9-1 and Figure 9-2 shows that the gas consumption during the week is higher than the gas production. However, during the weekend the consumption is lower than the gas production. Therefore, the gas content is repetitive on weekdays and increases over the weekend. Maximum gas content of 15.1 m³ is achieved on Monday morning when the gas tap is opened. During weekdays (except Monday morning) a maximum gas content of 7.7 m³ is achieved. Figure 9-2 clearly shows that the total biogas demand is too high for the biogas production. As a result, another stove running on LPG, firewood or charcoal will always be needed to support the biogas stove.

There are two options for sizing. The first option is to dimension the gasholder for the maximum gas content throughout the weekdays, i.e. without taking weekends into account. This maximum gas content is approximately 7.7 m³. This is about 65% of the daily gas production. The second option is to dimension the gasholder for the maximum gas content throughout the whole week, i.e. with weekends taken into account. The maximum gas content over the whole week is 15.1 m³ on Monday morning before cooking is started. This is about 127% of the daily gas production. The main difference between the two options is that the first option allows full biogas cooking on Saturday and Sunday and the second option on Saturday, Sunday and the first cooking period on Monday morning. However, with the second option almost double the gas content can be captured on Sunday. This extra gas can be used on Monday and is, therefore, an added value.

Note that these volumes are for standard conditions (25°c and 1 bar). The actual temperature and pressure will both be higher, approximately compensating for each other, but these do not differ much from the standard conditions. A correction for the volume given the assumptions made and the relatively large uncertainty on the result would therefore not be an added value.

9.4 Designing and calculating the size of the gasholder

This section discusses the design and calculating of the gasholder. The results of the simulation discussed in section 9.3.4 are used in order to dimension the gasholder. The gas storage present in the hybrid installation will be taking into account when determining the size of the external gasholder. The paper 'Technical evaluation and standardization of biogas installation in Ghana' defines a rule of thumb for the gasholder volume.

> The designer must choose a gasholder volume that is capable of accepting the volume of gas produced at a time, capable of accepting gas produced between periods of gas consumption, and capable of compensating for daily fluctuations (75-125% of calculated gas produced) [20, p. 52].

At the end of this section, the gasholder is dimensioned and designed corresponding to the design discussed in section 5.4.

9.4.1 Design of the gasholder

As discussed in section 5.4, a floating-drum gasholder is chosen. The gasholder consists of two concentric cylinders, shown in Figure 9-3. These cylinders are usually made out of concrete. The opening between these two cylinders is filled with water. A metal drum (shown in Figure 9-3) is placed between these two cylinders, which then floats on the water.

Figure 9-3: Concentric cylinders in Senegal

Figure 9-4: Floating-drum gasholder in senegal

The top of the gasholder should be slightly sloped so that rainwater can drain off from the top so that the top is not extra vulnerable to rust due to water on the top. The top should not be very steep, as this is unnecessary and involves additional costs. The gas pressure and the weight of the drum only cause tensile forces in the jacket sheet. No reinforcement is required to withstand these forces [23].

As mentioned earlier, the drum is placed between two concentric cylinders. The height of the sidewall should be as high as the cylinders, if the walls of the cylinders are too high this only leads to unnecessary construction costs. Because the drum floats in the water between the two cylinders, the drum can tilt and therefore rub against the cylinder, this can damage the paint and the drum and is therefore disadvantageous for the lifespan of the drum. In order to prevent damage to the drum, a guide frame is needed or some kind of padding, directly attached to the outer shell of the drum. If a guide frame is chosen, the guide frame must be designed so that the gas drum can be removed for maintenance. In order to remove the drum, air needs to be able to flow in the drum, this can be done by either emptying the water jacket or uncoupling the gas pipe and opening the valve [23].

In order to have the largest possible gas storage, the water jacket must be filled to the top, otherwise, the gas storage will reduce, because the drum can rise less high without being raised above the water jacket. So, if the water evaporates, gas storage decreases. For this reason, the water level must be checked regularly. A simple trick to prevent the water from evaporating as quickly is adding a few drops of oil to the water. When oil is added to the water it must be ensured that excess water does not carry oil during the rainy season, thus releasing oil to the ground. This can be prevented by using an overflow pipe as shown in Figure 9-5.

Figure 9-5: Overflow pipe

An important comment is that the water jacket must be kept free at any time to allow the drum to move freely without extra resistance. It is also recommended that the distance between the inner and outer cylinder is wide enough (>15 cm) to allow to retrieve objects which have accidentally ended up between the cylinders. Depending on the technique used to make the cylinders, the cylinders may not be perfectly round, in order to avoid rubbing the drum against the cylinders, extra spacing must be provided between the two cylinders. Because an external gasholder is used, the gasholder can more easily be designed and build bigger than with a built-in gasholder, but if the drum is too high and the drum rests on the bottom, the weight of the gasholder cannot provide extra pressure, so the last gas present in the gasholder cannot be used. The useful gas volume in the gasholder is therefore only the volume of the drum without the sloped roof.

9.4.2 Material of the drum

The drum can be made out of various materials. Usually, the drum is made of a 2.5 mm steel sheet for the sides and a 2 mm sheet for the top. Steel is prone to corrosion, so even with maintenance, the lifespan of the drum is only about 5 years in tropical coastal regions. Because of the short lifespan of a steel drum, steel is not an option. A good alternative that can be used, is glass-fiber reinforced plastic and high-density polyethylene, but these materials have higher construction costs than a steel drum [23]. The availability of these materials is also more limited, so transport or import costs can increase the total cost if these materials are not available locally. Another alternative is stainless steel, the material costs are higher than steel, but stainless steel is more rustproof than steel. However, stainless steel is not completely rustproof and therefore requires annual maintenance, which results in an annual maintenance cost for the paint. However, a longer lifespan than 5 years can be expected.

In order to guarantee the longest possible lifespan of the gasholder, glass-fiber reinforced plastic or high-density polyethylene is best to be used for the drum. These materials are non-corrosive, which is an important factor in coastal areas. Both materials are available locally in Mombasa, so there are no additional import costs for this project. The PUXIN digester discussed earlier uses a glass-fiber reinforced plastic gasholder that has an expected lifespan of 10 years. A similar lifespan can be expected for a drum made of glass-fiber reinforced plastic.

The options discussed require the drum to be completely custom-made. This means that, in addition to the material costs, labor costs are also incurred. Another option is to purchase a standard water tank, as shown in Figure 9-6. These are widely available in Mombasa and are frequently used. A common brand of these water tanks in Mombasa is Top Tank [57].

Figure 9-6: Water tank from Top Tank [57]

The water tank from Top Tank is made from food-grade polyethylene with extra 2.5% carbon black compounded material for durability. The tank is double layered with an inner white layer. This white inner layer makes inspection and maintenance easier, as dirt can be seen more easily. The outer layer protects against UV penetration. The water tanks from Top Tanks have a lifespan of up to 25 years, which is similar to the lifespan of the fixed-dome plant [57].

An important difference between a steel and plastic drum is the weight. The pressure of the biogas in the gasholder (500-2,000 Pa depending on the gas stove and pressure losses) is caused by the weight of the drum. The specific weight of steel is 2.5-4.4 times more than that of fiber-reinforced Polymer Composites (depending on the type of fiber and steel) [58] and 5.5 to 8.9 times more than that of polyethylene (depending on the type of polyethylene and steel) [59]. The drum will therefore have to be made heavier (when using a plastic drum) to create the required pressure. There is chosen to make the drum out of a water tank, because of the discussed advantages such as long lifespan, UV resistance, suitability against extreme weather conditions, and no construction costs.

9.4.3 Determining the gasholder volume

As mentioned in section 9.3.4 there are two options for sizing the gasholder. Sizing the gasholder for just weekdays or for the gas content peak in the weekend. In order to make maximum use of the biogas, the gasholder is dimensioned for the peak. The peak gas content is 15.1 m^3.

In order to determine the size of the external gasholder, there need to be looked at the size of the gas storages present in the hybrid installation. These gas storages are present in the fixed-dome digester, the covered overflow tank and in the flexi biogas installation. An overview is given in Table 9-4.

Table 9-4: Overview of the gas storages present in the hybris installation

Digester	Gas storage
Fixed-dome	1.5 m^3
Covered overflow tank	2.0 m^3
Flexi	4.0 m^3
Total	7.5 m^3

The total gas that can be stored in the hybrid biogas installation is 7.5 m^3. This means that a minimum of 7.6 m^3 has to be stored inside the external gasholder. When taking into account a 20% safety margin (total gas storage of 18 m^3) 10.4 m^3 has to be stored inside the external gasholder. As mentioned in section 9.4.2 a water tank will be used. Such a water tank has standard dimensions and volumes. The standard volumes a water tank close to 10.4 m^3 are 8m^3, 10m^3 and 15m^3 [57]. A volume of 10 m^3 is chosen. Taking into account the bottom that has to be cut away and the sloping top that cannot be compressed, the useful volume of the gasholder is about 9m^3. This is results in a safety margin of approximately 10%, which is sufficient. The dimensions of a 10 m^3 tank from Top Tank are: diameter = 226 cm and height = 243 cm [57].

10 Practical implementation of the biogas installation

This chapter discusses the progress of the project and the remaining tasks that still need to be completed. It then discusses how the startup of the installation will proceed. To conclude, the maintenance of the plant is addressed.

10.1 Progress of the constructions

After a long procurement process, the work for the biogas installation could begin on March 31st. The work started with the excavation for the fixed-dome digester. A few days later, the first problems occurred. During the excavation, a septic tank and several pipes including an internet cable appeared as shown in Figure 10-1. The removal of the septic tank and the piping took a week after which the pit had to be enlarged so that the digester would be able to fit.

Figure 10-1: Removal of the septic tank and the piping

In mid-April, the materials for the fixed-dome digester were delivered. These consisted mainly of cement, sand and gravel. Also the materials for the fence that will be placed around the biogas site were delivered (Figure 10-2). Meanwhile, the orders for the flexi biogas installation and the cover for the overflow tank were also placed. In this way, these materials would also be delivered on time so that when the fixed-dome was finished, work could continue on the rest of the biogas installation.

Figure 10-2: Materials for the fixed-dome digester and for the fence

On April 19th, the effective work on the fixed-dome digester was started. This began with the excavation of the conical bottom after which the foundation could be placed. Then the walls of the digester could be built as shown in Figure 10-3.

Figure 10-3: Conical bottom and walls of the fixed-dome digester

Once the walls were in place, the dome of the digester could be constructed. When this was finished, construction of the overflow tank continued (Figure 10-4).

Figure 10-4: Overflow tank

In late April, the fixed-dome was finished with waterproof plaster (Figure 10-5). This was not applied over the entire overflow tank which was necessary to prevent moisture penetration. This was corrected afterward. They had also placed the inlet reservoir in our absence so it was not placed at the correct height. The inlet reservoir should be placed higher to ensure the operation of the biogas installation.

Figure 10-5: Overflow tank and inlet reservoir

In the middle of May, the inlet reservoir was raised, ensuring the operation of the installation. Also, the overflow tank was further finished with waterproof plastering. The dome of the digester was given a dark layer of paint in order to maximally capture the heat of the sun. In addition, the flexi biogas installation was placed. This was placed 70 cm lower than the outlet of the fixed-dome digester to guarantee the flow of the biomass. Works for the gasholder were also started. The outer cylinder of the two concentric cylinders was already constructed. The progress of the construction of the biogas installation is shown in Figure 10-6.

Figure 10-6: Progress of the construction: a) inlet b) fixed-dome digester c) flexi biogas installation d) inside of flexi biogas installation

At the completion of this master's thesis on May 17, 2021, the status of the project at that time is shown in Figure 10-7. A detailed discussion of the preliminary installation is done in section 11.2.

Figure 10-7: Status of the project on May 17, 2021

The project was therefore not fully completed during the stay in Mombasa. Lengthy administration and procurement processes caused delays in the construction of the biogas installation. Because this project is part of a larger project of VLIR-UOS [60] that runs until August 2022, there is still sufficient time to complete the biogas installation. The tasks still to be completed are listed below:

- The overflow tank is constructed but still needs to be covered. In this way, the gas produced in this tank will be captured;
- The outer cylinder of the two concentric cylinders had already been constructed. The next step is the construction of the inner cylinder. A tank has already been purchased that will serve as a floating drum. It still needs further modification and reinforcement to be fully functional;
- A digestate tank has yet to be fully constructed. The hole needs to be dug and the tank itself needs to be constructed with bricks;
- A final step consists of providing the fixed-dome digester, the flexi biogas installation, the covered overflow tank and the gasholder with piping that will be connected to the stoves in the scullery.

10.2 Start-up of the installation

Once the biogas installation is ready and the stoves are connected, the installation can be started up. This start-up cannot be done directly with the organic food waste from the university. This is because the bacteria required for the anaerobic digestion process are not yet present. For this reason, the start-up of the plant should be done with biomass that already contains bacteria. This is called inoculating the digester. The addition of bacteria can be done in several ways. Digestate from other digesters in the area can be used or diluted cow dung can be used. For the biogas installation at the university, digestate from other digesters will serve as feeding for the digester for the start-up.

The digestate must be diluted with water, the ideal ratio is 1:1. The minimum amount of digestate required for the startup of the digestion process is 10% of the total active reactor volume. This may always be more as long as the active reactor volume of 12 m^3 is not exceeded. During the start-up phase, the bacteria population needs to be gradually acclimatized to the feedstock. It is therefore important to gradually increase the amount of feed load fed to the digester daily. In this way, it is possible to obtain a balanced microbial population.

10.3 Maintenance

A well-designed biogas installation should be easy to maintain. Nevertheless, daily care is necessary to ensure proper gas production and a long lifespan of the installation.

10.3.1 Feeding the digester

The first task to be performed is the collection of organic waste. If organic waste is collected from different places, it is important that it is made clear that only organic waste should be put into the collection bucket/container. If this important requirement is not respected by the source of the waste, there will be many impurities in the waste.

The amount of biomass that is added to the digester needs to be checked and measured. In order to obtain stable gas production, the digester must be fed regularly. Before the kitchen waste is added to the digester, the waste must be treated. This treatment consists of reducing the size of the particles to about 3-5 cm. This can be done using a shredder. Even if an electric shredder is used, the shredding of the organic waste is a time-consuming process. The large pieces of waste, such as a head of lettuce, must be pushed through the shredder one by one (depending on the size of the shredder). However, not all types of waste have to be shredded. The kitchen waste consisting of vegetables such as lettuce should definitely be shredded. Food waste such as beans or rice does not have to be shredded. For this reason, food waste in the kitchen should be sorted into two containers/buckets. One for waste to be shredded and one for waste not to be shredded. Which type of food waste should be shredded is determined by experience. For example, if a non-shredded type of food waste is difficult to move from the inlet to the digester, it is best to shred it. A list of food types that should or should not be shredded can therefore hardly be given. However, the knowledge and experience of biogas installations in other places can be used.

In addition, impurities have to be removed to avoid scum formation and blockage of the inlet and outlet pipes. It is best to remove these impurities at the source (the kitchen). If this is not done properly, removing these impurities from the waste is a time-consuming task and impurities will always remain. Also, water has to be added. The biomass to water ratio should be around 1:3. This mixture can then be fed to the digester [9], [41]. However, it is not necessary to measure this ratio accurately. The staff, responsible for the biogas installation, will develop experience and a feeling for the necessary amount of water by sight and the force he/she has to apply when stirring the mixture. A good comparison that can be made is that the structure of the mixture should be yogurt-like. It is important to stir well with a stick while adding the water in order to get a homogeneous mixture.

10.3.2 Removing the digestate

The digestate leaving the digester must be removed and processed several times a week. It is best to do this daily. The amount of digestate produced daily is equivalent to the normal daily feeding load. The appearance and odor of the digested slurry need to be checked on a regular basis. If well digested, the effluent should not have an acidic odor (this would be an indication of overload or imbalanced microorganism population). Checking the pH of the digested slurry by means of litmus paper or a pH meter can help to examine biological activity. However, it is worth noting that the pH value of the digestate only indicates instability of the anaerobic process when the substrate-specific buffer capacity has already been consumed. If the pH is below 5.5, feeding has to be stopped and only started again with a gradually increasing feeding rate once the pH has stabilized [9, p. 45].

10.3.3 Other tasks

The tasks that should be performed on a regular, weekly or monthly basis are [9]:

- cleaning biogas stoves;
    - Removing food particles and dust.
- checking the gas tightness of gas pipes, joints, valves, fittings and stove;
    - Gas leaks can be detected by the smell of biogas because the gas contains small amounts of hydrogen sulfide that smells like rotten eggs.
    - Leaks can also be detected by smearing some liquid detergent on the spot where leakage can be expected. If there are leaks, bubbles will be observed in those areas. To avoid danger to kitchen staff, leaks must be repaired immediately.
- removal of condensed water;
    - Condensed water must be removed to prevent the blockage of the pipes.
- cleaning the digesters;
    - Dust and sand (especially with the flexy digester) can cause wear.
- checking the water level in the gasholder.
    - The water between the two concentric cylinders evaporates slowly.

Steps that can be taken in the event that gas production is interrupted are [9], [41]:

- Checking the gas tightness of gas pipes, joints, valves, fittings and stove;
    - Measure the pressure at the fire (minimum 100 mbar) and close the valve at the digester. The pressure should not drop more than 5 mbar. If it does, there is a leak that can be detected as described above.
- Checking the fermentation process;
    - If no gas is produced and the slurry smells sour, the digestion process may be disturbed. Wait to feed the digester (maximum 4 weeks). If gas production does not resume, the digester will have to be emptied and restarted.
- Checking the gas tightness of the fixed-dome.
    - Close the tap on the digester. Wait one day to allow pressure to build up. Gas production can be seen by gas bubbles in the inlet and outlet. If not, there may be a leak that occurs with increased pressure or a crack in the dome. In the latter case, the plant must be emptied and cracks must be repaired.

The problem with scum is that it is difficult to remove and therefore better to be prevented. This must be done by proper pre-treatment in which straw and other impurities are removed and sufficient water is added.

Scum can be avoided by stirring every hour, day and night. This is only possible with an automated mechanism and therefore only possible for large installations. The formation of a scum layer is avoided in this project by the gas tap regulation discussed in section 9.3.3. By the daily up and down movement of the slurry in the digesters, the formation of a scum layer is avoided. When foam forms, it can be broken up, but this requires heavy equipment because it can become so solid after only a short time. It is also possible to remove the scum with water from above pushing it into the liquid. But this also requires expensive equipment. So, it is better to avoid scum by the proper feeding process [41].

11 Discussion

This chapter discusses the results and the predetermined design. This is followed by a discussion of the implementation of this design at the site. To conclude, future work is discussed and a conclusion is given.

11.1 Results of the calculations and simulations

This section summarizes the results of the calculations and simulations that were performed. The main focus is on the results related to the performance and design of the installation.

The most important inputs that determine the size of the digester are the daily available food waste (100 kg), the retention time (± 30days) and the biomass/water ratio (± 1:3). From these inputs it can be concluded that the active volume of the fixed-dome digester is 12 m³. This size is common in installations in Kenya. A daily gas production of 5.28 m³ can be expected for the designed fixed-dome digester with kitchen waste as feedstock. For the designed hybrid system, on the other hand, a daily biogas production of 11.88 m³ can be expected.

To determine the size of the gas storage, a simulation was performed that takes into account the consumption pattern and the daily gas production. This simulation concludes that the peak gas volume that needs to be stored is 15.1 m³. Taking into account the volume of gas that can be stored in the fixed-dome, covered overflow tank and in the flexi biogas installation, the external gasholder should be able to store 10.4 m³ of gas, taking into account a safety margin of 20%.

11.2 Design and implementation of the biogas installation

In this section, the design determined and discussed in this master's thesis is summarized, after which the final design of the installation as it was built in practice is discussed.

11.2.1 Theoretical design of the installation

The total installation consists of three parts: the fixed-dome digester, the additional systems leading to a hybrid installation and the external gasholder. The installation initially starts from a fixed-dome digester. This has been further expanded into a hybrid installation to deal with problems of the fixed-dome digester such as low efficiency.

The design of the fixed-dome system has many similarities to the Deenbandhu model, with the only difference being the bottom which is conical instead of spherical. This design ensures a structurally stable construction that is relatively easy to build.

In addition, the decision was made to cover the digester's overflow tank to reduce gas losses and greenhouse emissions. To further increase the efficiency of the plant, a flexi biogas installation has been added in series (behind the fixed-dome digester). This ensures that the slurry undergoes a more complete digestion process.

A floating drum is used for the gasholder. Its design is reasonably straightforward. For the drum, a water tank is used, as these are readily available in Mombasa and cheap compared to making it from scratch. A gasholder with a volume of 10 m³ is chosen, as this is a standard size for the water tank.

11.2.2 Implementation of the design

For various reasons, the installation built on the field differs from the designed installation. These differences are discussed in this section.

The inlet

The design of the inlet is shown in Figure 11-1. The top of the inlet is in total about 120 cm high. The hole of the inlet is positioned at a height of about 70 cm. There are steps and a platform to stand on. In this way, the food waste can be mixed easily and safely.

Figure 11-1: Inlet reservoir

The fixed-dome digester

The fixed-dome installation was built by an experienced contractor. This contractor normally always builds the same standard model (similar to the Akut fixed-dome digester discussed in section 4.1.4). This standard model uses a cylindrical chamber with a dome-shaped top. For this reason, the builders had no experience in building a biogas installation with a fermentation chamber consisting only of a large dome. Due to the lack of experience of the builders, the design of the fixed-dome digester was changed on-site in Mombasa. A technical drawing of the adjusted design of the fixed-dome digester is shown in Figure 11-2. The active volume of the digester is still approximately 12 m^3. The big difference is the cylindrical wall that was not present in the original design. This cylindrical wall will make the digester less structural stable in comparison with the original design.

During the construction of the fixed-dome digester, the construction workers made a mistake so that the result did not quite match the design. The dome is not perfectly round and the total height is 60 cm lower than the height according to the plan. Because of this, the digester has a volume of less than 12 m^3 and therefore the flexi digester had to be placed lower.

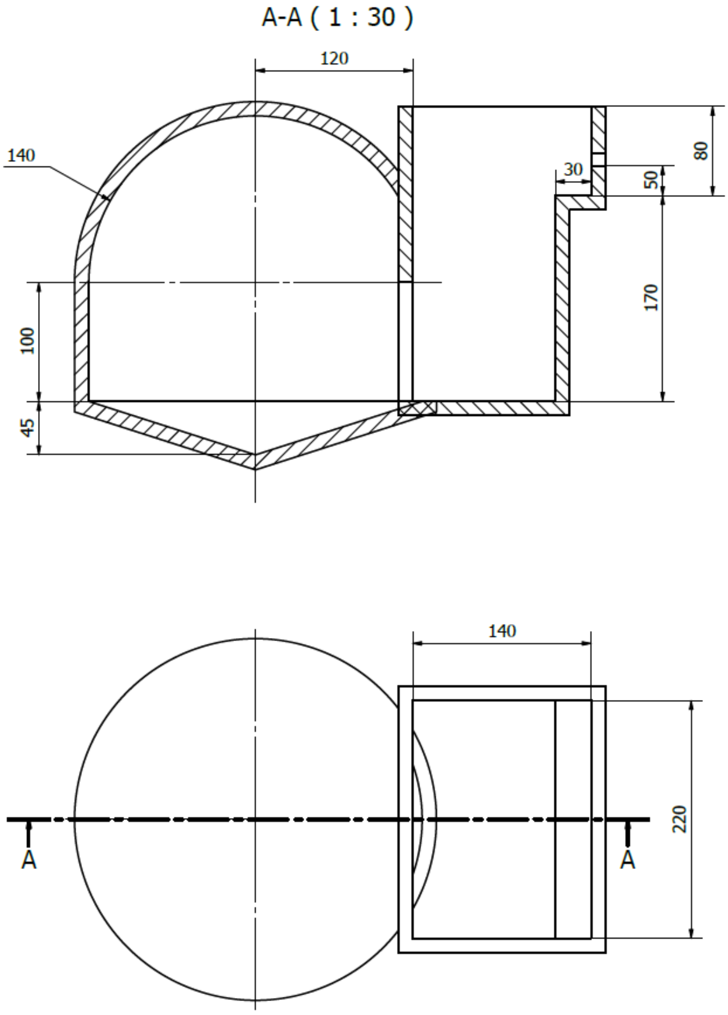

Figure 11-2: Technical drawing of the adjusted design of the fixed-dome digester

The built fixed-dome installation is shown in Figure 11-3. The digester is plastered with mortar mixed with black waterproof paint. The waterproof feature is to improve the durability of the plant. The black color is to improve the absorption of solar radiation to increase the digestion temperature.

Figure 11-3: Fixed-dome installation

The flexi digester

The installed flexi biogas installation is shown in Figure 11-4 (a, b and c). The UV filter, the net and the balloon can be seen in Figure 11-4c. The de-watering system for the flexi digester is done by the use of a plastic bottle and a T-piece, as shown in Figure 11-4d. The flexi digester is placed in a hole of three by seven meters as shown in Figure 11-4a and b. This hole is necessary so that the bottom of the flexi digester is about 70 cm lower than the outlet of the fixed-dome digester. This hole was originally not planned but because the outlet of the fixed-dome digester has been lowered, the flexi digester had to be lowered as well.

Figure 11-4: Flexi biogas installation a) front b) back c) inside of the digester d) dewatering system

The gasholder

The gasholder is the part of the installation that is the least complete. The progress of the gasholder at the time of leaving Mombasa (17th of May 2021) is shown in Figure 11-5. The outer cylinder of the gasholder is shown in Figure 11-5 and the water tank is shown in Figure 11-6. As mentioned in section 9.4.3, a water tank with a volume of 10 m³ is chosen. But due to problems with the procurement process and a limited budget, a water tank of only 2.5 m³ was purchased. As a result, not all biogas can be captured at all times.

Figure 11-5: Outer cylinder of the gasholder

Figure 11-6 Water tank that is going to be used for the drum

The design of the 2.5 m³ gasholder is shown in Figure 11-7. This figure shows the dimensions of both the concrete cylinders and the drum. Two taps will be placed at the bottom of the concrete cylinders. These taps, together with the slope, ensure that the water between the cylinders can completely be removed if this should ever be necessary in the future.

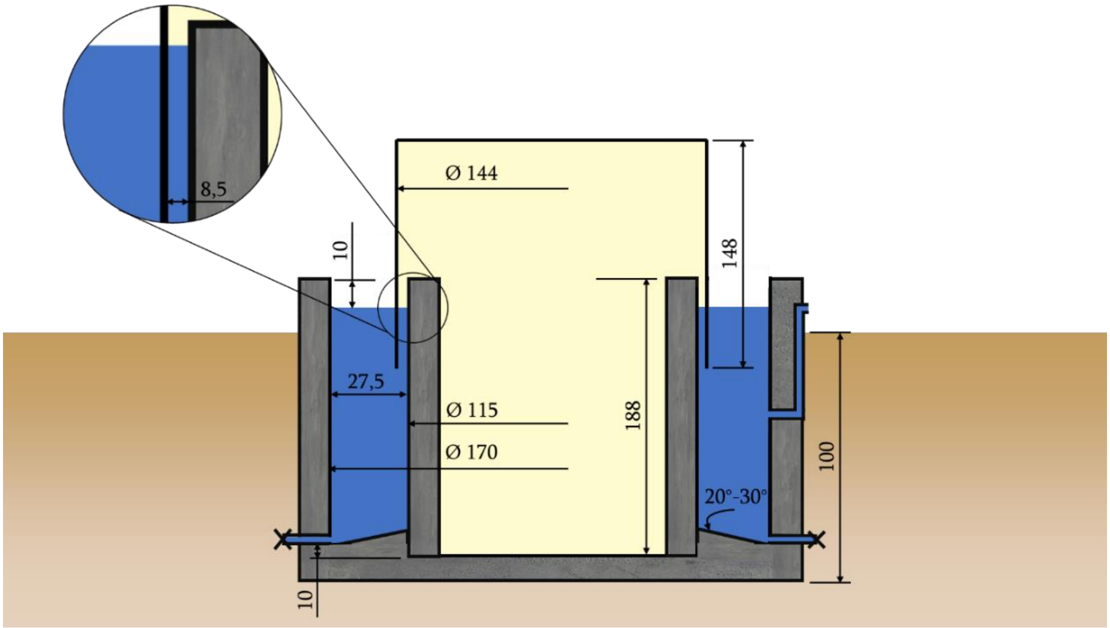

Figure 11-7: Design of the 2.5 m³ gasholder (dimensions in cm)

11.3 Future work

The biogas installation has made it possible to establish a Renewable Energy and Climate Change Research Center (RECCREC) in TUM, which will give additional research potential to the biogas installation. Depending on the financial resources made available for RECCREC, the biogas installation will be expanded with various sensors for monitoring gas production and consumption, but also for monitoring the quality of the gas (e.g. methane content) and of the digestate.

In the beginning, the analysis of the quality of the gas and the digestate will be done in cooperation with Taita Taveta University (TTU) [61]. TTU has various measuring and analysis devices for analyzing the quality of the gas, digestate and feedstock. The long-term goal of RECCREC is that all these measurements and analyses can be done in RECCREC.

RECCREC is also currently recruiting a PhD-student for the biogas installation. The student's task is to analyze and monitor the biogas installation. A PhD-student together with RECCREC is a good start for academic research on the biogas installation and on innovations in biogas technology in general.

Once the installation is operational and gas is produced, the gas production will be measured for each tapping point. Based on these measurements, the theoretically calculated gas production can be verified, as well as the efficiency of the different parts of the hybrid biogas installation. Unfortunately, the biogas installation will not be operational in time, therefore the measurement results cannot be processed in this master’s thesis. However, a research paper is written that discusses the design of the biogas installation, the hybrid plant in detail, the gasholder and the simulation. The paper will mainly be focused on the innovative aspect of the biogas installation and on the calculation. The paper will be published in the “Multidisciplinary Journal of Technical University of Mombasa Vol. 1 No. 2” [62] in 2021 and will be subjected to a standard peer-review process prior to publication. In appendix B, the research paper for the journal is added. Once the measurement results are available, students of TUM will incorporate them into a paper to be published in the same journal.

This master's thesis is part of a larger project of VLIR-UOS [60], the larger project runs until August 2022. The next steps in the larger project are the dissemination of the designed technology, the creation of a course around the installation and the start-up of a PhD around the setup. As mentioned before, the biogas installation will also be expanded in the future with several sensors for measuring gas production and for analyzing the quality of the gas. The construction of the entire biogas installation will be completed in June 2021.

11.4 Conclusion

This master's thesis focused on two major problems that occurred in cooking at the Technical University of Mombasa. One of them is the use of fossil fuels which are expensive and contribute to global warming. Another problem faced is the management of large amounts of organic food waste. To address these problems a biogas installation was designed and implemented.

The total installation consists of three parts: the fixed-dome digester; the extensions leading to a hybrid installation and the external gasholder. The fixed-dome installation is designed to be as structurally stable as possible. Due to the low efficiency and high gas losses of the fixed-dome digester, it was decided to expand the installation to a hybrid installation to solve these problems. In this way, the installation is also more suitable for educational purposes for the Technical University of Mombasa. The extension to a hybrid installation consists of a cover for the overflow tank and a flexi biogas installation. These extensions increase the efficiency of the installation and ensure that the biomass undergoes a more complete digestion process. The produced gas will be stored in the fixed-dome digester, the covered overflow tank, the flexi biogas installation and in the external floating-drum gasholder. The gas coming from the fixed-dome digester, the flexi biogas installation and from the covered overflow tank will be transported to the external gasholder. This external gasholder ensures that the biogas is delivered to the biogas stove at a constant, desired pressure. The biogas installation (as originally designed) is expected to produce 11.88 m^3 of biogas per day. This is good to cover 27% of the scullery's energy demand. It was originally anticipated for the installation to be able to collect and store the gas peaks (which follows from the simulation), however, due to the smaller gasholder used in TUM, the highest gas peaks cannot be captured and stored.

At the time of departure to Belgium, the plant was mostly ready (as shown in Figure 10-7) but some tasks still need to be completed. Therefore, at the time of writing, the works on the biogas installation are still in progress. As the project is part of a multi-year project, the continuation of the works is guaranteed. Close consultation is taking place with the university staff in order to bring the implementation of the biogas installation to a successful end.

Figure 11-8: Status of the project on May 17, 2021

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13 Appendices

Appendix A: Simulation of gas production and consumption

```
"""
#############################################
Simulatie gasproductie biogasinstllatie
#############################################
@author: Daan Vanhoudt & Tobias Corthouts
"""
import pandas as pd
import numpy as np
import math as m
from matplotlib import pyplot as plt

# Inlezen van het CSV-bestand
dfBiogas = pd.read_csv("Simulatie_gasproductie_biogasinstllatie.csv", sep=";",
encoding='latin-1')


"""
Deze functie berekend of m een velvoud is van n

:param m
:param n
"""
def isMultiple(m, n):
    # Returns true indien m een veelvoud is van n
    return True if m % n == 0 else False

"""
Deze functie print de data van een grafiek naar een csv bestand

"""
def toCsv(x, y, naam):
    # Dictionary of lists
    yRound = [round(num, 2) for num in y]
    dict = {'inhoud': yRound, 'tijd': x}

    df = pd.DataFrame(dict)

    # Saving the dataframe
    df.to_csv(naam)


"""
Deze functie berekent a.d.h.v. de gebruikte hoeveelheden hout en kool het equivalent
biogasverbruik.
:param hout: gebruikte hoeveelheid hout [kg]
:param kool: gebruikte hoeveelheid kool in [kg]
:param duur: duur van de kookperiode in minuten
:param q: energiebesparing door gebruik te maken van voorverwarmd water [J]
:param correctiefactor: factor die het verbruik in het weekend reduceerd
:return: biogasverbruik [m³ biogas / min]
"""
def berekenBiogasequivalent(hout, kool, duur, q, correctiefactor):

    verbruikPeriode = hout * 0.276 + kool * 0.666           # Equivalent biogasverbruik
tijdens de kookperiode
    verbruikMinuut = verbruikPeriode/duur                   # Equivalent biogasverbruik per
minuut voor de kookperiode
    besparing = q / (21.48 * 10 ** 6) / 20                  # Biogas besparing door gebruik
van voorverwarmd water

    return (verbruikMinuut - besparing) * correctiefactor


"""
Deze functie berekent voor een bepaalde opgegeven periode per minuut het biogasverbruik.
:param temp: temperatuur van het voorverwarmde water [°C]
:param xAs: de gewenste duur van de simulatie [minuten]
:param beginKookperiode: lijst met tijdstippen van het begin van de kookperioden
:param eindKookperiode: lijst met tijdstippen van het einde van de kookperioden
:return: een lijst van het biogasverbruik over de volledige duur van de simulatie
"""
def berekenBiogasVerbruik(temp, xAs, beginKookperiode, eindKookperiode):

    biogasVerbruik = []
    begin = 0
    kookperiode = 0
```

```
    hout = 0
    kool = 0
    duur = 1

    for minuten in xAs:
        dag = 1 + m.floor(minuten / 1440)                   # Dag bepaald door het aantal
minuten (eerste dag is dag 1)

        if isMultiple(dag + 1, 7):                          # Controleren of het zaterdag is
            correctiefactor = 0.2                           # Zaterdag is de consumptie 80%
minder dan door de week
        elif isMultiple(dag, 7):                            # controleren of het zondag is
            correctiefactor = 0.1                           # Zondag is de consumptie 90%
minder dan door de week
        else:
            correctiefactor = 1                             # Op een weekdag is de
correctiefactor 1

        controleTijdstip = minuten - 24 * (dag - 1) * 60    # Tijdstip herlijden naar
hetzelfde tijdstip op dag 1

        # Consumptie berekenen voor iedere minuut door na te gaan binnen welke kookperiode we
ons bevinden
        if beginKookperiode[0] <= controleTijdstip < eindKookperiode[0]:    # Kookperiode 1
            begin = beginKookperiode[0]
            eind = eindKookperiode[0]
            duur = (eind - begin)
            kookperiode = 0

        elif beginKookperiode[1] <= controleTijdstip < eindKookperiode[1]:  # Kookperiode 2
            begin = beginKookperiode[1]
            eind = eindKookperiode[1]
            duur = (eind - begin)
            kookperiode = 1

        elif beginKookperiode[2] <= controleTijdstip < eindKookperiode[2]:  # Kookperiode 3
            begin = beginKookperiode[2]
            eind = eindKookperiode[2]
            duur = (eind - begin)
            kookperiode = 2

        elif beginKookperiode[3] <= controleTijdstip < eindKookperiode[3]:  # Kookperiode 4
            begin = beginKookperiode[3]
            eind = eindKookperiode[3]
            duur = (eind - begin)
            kookperiode = 3

        elif beginKookperiode[4] <= controleTijdstip < eindKookperiode[4]:  # Kookperiode 5
            begin = beginKookperiode[4]
            eind = eindKookperiode[4]
            duur = (eind - begin)
            kookperiode = 4

        # Energiebesparing door gebruik te maken van voorverwarmd water wordt over de eerste
20 min verdeeld
        if begin + 20 > controleTijdstip:
            hout = dfBiogas.loc[kookperiode, "hout"]
            kool = dfBiogas.loc[kookperiode, "kool"]
            volume = dfBiogas.loc[kookperiode, "volume"]
            # Energiebesparing door water vanaf een temperatuur hoger dan 20°C te laten koken
                # Deze hogere temperatuur wordt bereikt door een solar heater die geplaats
wordt in het kader
                # van een andere masterproef
            q = volume * 4186 * 0.99 * (temp - 20)
            # De equivalente biogas consumptie wordt berekend (rekening houdend met de eerder
vermelde energiebesparing)
            consumptie = berekenBiogasequivalent(hout, kool, duur, q, correctiefactor)
        else:
            consumptie = berekenBiogasequivalent(hout, kool, duur, 0, correctiefactor)

        biogasVerbruik.append(consumptie)                   # Lijst van de consumptie per
minuut

    return biogasVerbruik


"""
Deze functie berekent de gasinhoud van de gashouder, m.a.w de hoeveelheid gas iedere minuut.
:param productieMinuut: biogasproductie [m³ biogas / min]
```

```
:param consumptie: een lijst van het biogasverbruik over de volledige duur van de simulatie
:param kraanOpen: tijdstip waarop de kraan open gaat [min]
:param kraanToe: tijdstip waarop de kraan toe gaat [min]
:param xAs: de gewenste duur van de simulatie [min]
:param beginKookperiode: lijst met tijdstippen van het begin van de kookperioden
:param eindKookperiode: lijst met tijdstippen van het einde van de kookperioden
:return: een lijst die de beschikbare hoeveelheid gas per minuut geeft
"""
def berekenGasinhoud(productieMinuut, consumptie, kraanOpen, kraanToe, xAs, beginKookperiode,
eindKookperiode):
    # De totale biogasproductie als de kraan van de biogasinstallaties naar de gashouder toe
is
    productieKraanToe = productieMinuut * (24 * 60 - (kraanToe - kraanOpen))
    yAs = []
    for minuten in xAs:
        if minuten == 1:
            inhoud = 0                                          # In het begin is de inhoud 0
        else:
            inhoud = yAs[minuten-2]                             # Inhoud van vorig tijdstip

        dag = 1 + m.floor(minuten / 1440)                       # Dag (bepaald door het aantal
minuten (start = 1))
        controleTijdstip = minuten - 24 * (dag - 1) * 60        # Tijdstip herlijden naar
hetzelfde tijdstip op dag 1

        # Gas productie aan de inhoud van de gashouder toevoegen
        if kraanOpen < controleTijdstip <= kraanToe:            # Controle of de kraan open
staat
            inhoud = inhoud + productieMinuut                   # Als de kraan open staat
wordt de minuut productie toegevoegd
        elif controleTijdstip == kraanOpen:
            inhoud = inhoud + productieKraanToe                 # Als de kraan open wordt
gezet, wordt de productie terwijl de kraan toe was toegevoegd

        # Controleren of we in een kookperiode zitten
        if beginKookperiode[0] <= controleTijdstip < eindKookperiode[0] or beginKookperiode[1]
<= controleTijdstip < eindKookperiode[1] or \
            beginKookperiode[2] <= controleTijdstip < eindKookperiode[2] or
beginKookperiode[3] <= controleTijdstip < eindKookperiode[3] or \
            beginKookperiode[4] <= controleTijdstip < eindKookperiode[4]:

            if inhoud - consumptie[minuten-1] < 0:              # Inhoud kan niet kleiner zijn
dan 0
                inhoud = 0
            else:
                inhoud = inhoud - consumptie[minuten-1]         # Totale inhoud wordt
verminderd met de consumptie

        yAs.append(inhoud)

    return yAs


"""
Gebruikt bevenstaande functies om op ieder moment de hoeveelheid biogas weer te geven
gedurende een bepaalde periode
:return: grafiek met de hoeveelheid biogas in functie van de tijd
"""
def simulationBiogas():

    productieDag = dfBiogas.loc[0, "Q_biogas_fixed_dome"]   # Productie per dag
    productieMinuut = productieDag/24/60                    # Productie per minuut

    beginKookperiode = list()                               # Lijst voor de beginperiodes
    eindKookperiode = list()                                # Lijst voor de eindperiodes

    # lijsten vullen met gegevens uit het CSV-bestand
    for teller in range(0, 5):
        beginKookperiode.append(dfBiogas.loc[teller, "Begin_kookperiode"] * 60)
        eindKookperiode.append(dfBiogas.loc[teller, "Eind_kookperiode"] * 60)

    # Moment wanneer de kraan van biogasinstallatie naar de gashouder open staat
    kraanOpen = dfBiogas.loc[0, "Kraan_open"] * 60          # Uur dat de kraan naar de
gashouder wordt open gezet
    kraanToe = dfBiogas.loc[0, "Kraan_toe"] * 60            # Uur dat de kraan naar de
gashouder toe wordt gezet

    # Temperatuur van het water
    temp = dfBiogas.loc[0, "temp"]                          # De gemiddelde temperatuur van
```

```
het water

    SimulatieDuur = 14                                      # Duur van de simulatie in dagen
    duurMinuten = SimulatieDuur * 1440                      # Duur van de simulatie in minuten
    xAs = range(1, duurMinuten, 1)

    # Een lijst van de consumptie berekenen
    consumptie = berekenBiogasVerbruik(temp, xAs, beginKookperiode, eindKookperiode)

    # Een lijst van de gasinhoud bereken
    yAs = berekenGasinhoud(productieMinuut, consumptie, kraanOpen, kraanToe, xAs,
beginKookperiode, eindKookperiode)

    # Figuur plotten
    plt.plot(xAs, yAs, "-", label="Gas content", color="#003366", linewidth="1")

    plt.title("Total gas content")
    plt.xlabel("Duration [days]")
    plt.ylabel("Gas content [m³]")
    plt.grid()

    ticks = list(range(0, duurMinuten, 1440))  # points on the x axis where you want the label
to appear
    labels = "Mon Tue Wed Thur Fri Sat Sun Mon Tue Wed Thur Fri Sat Sun".split()
    plt.xticks(ticks, labels)

    plt.show()

    # Extra's
    print("De maximale gasinhoud is:", round(max(yAs), 3), "m³")

    toCsv(xAs, yAs, 'Gasinhoud.csv')
    toCsv(xAs, consumptie, 'Consumptie.csv')


simulationBiogas()
```

Appendix B: Medium-sized hybrid biogas installation consisting of a fixed-dome and flexi biogas installation: design, simulation and performance evaluation

Medium-sized hybrid biogas installation consisting of a fixed-dome and flexi biogas installation: design, simulation and performance evaluation

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A biogas installation is being designed and implemented for the Technical University of Mombasa. The installation processes organic waste from the kitchen in the most optimal way and will produce biogas that will be used for cooking and digestate that will serve as a fertilizer. This installation starts from a fixed-dome digester that is dimensioned according to the available biomass. The active volume of the digester is 12 m³ and the expected biogas yield is 5.28 m³/day. To take into account the disadvantages of the fixed-dome digester such as its low efficiency, the digester is extended to a hybrid installation. The possibilities for the hybrid installation and the disadvantages of the fixed-dome digester were investigated in an extensive literature study, described in the master's thesis "Design and implementation of a hybrid biogas installation to reduce environmental pollution and food waste" (Corthouts & Vanhoudt, 2021). The extension of the fixed-dome digester to the hybrid biogas installation will be done by covering the overflow tank in order to absorb the gas losses that occur here. In addition, a flexi biogas installation is placed behind the fixed-dome digester. In this way, the biomass undergoes a more complete digestion process. The total gas production of the hybrid installation is estimated at 11.88 m³/day. Using a simulation, the volume of the floating-drum gasholder that will be added to the installation will be determined. The volume of gas that should be able to be stored in it amounts to 10.4 m³.

Key words: biogas, fixed-dome digester, flexi biogas installation, hybrid biogas installation, floating-drum gasholder

Introduction

In Kenya there are mainly 3 types of digesters: fixed-dome, floating-drum and balloon-type digesters (Kenya biogas plan). Originally, starting from 1970, only the fixed-dome and floating-drum digester were installed in Kenya (Gitonga, 1997), but now (2021) the Kenya biogas program is also promoting and supporting balloon-type digesters. Therefore, balloon-type digesters are becoming more common in Kenya, especially in newer installations. The most common balloon-type digester used in Kenya is a flexi biogas installation and is one of the most recent innovations concerning biogas. Flexi biogas installations in Kenya are mainly made and distributed by the company 'Flexi biogas solutions' (Flexi Biogas Solutions, sd), which also have patents on various flexi biogas technologies. Despite the promising future of flexi biogas installations, fixed-dome digesters are still very common in Kenya and in other developing countries, in new and existing installations. However, in contrast to the balloon-type digester, fixed-dome digesters have no recent innovations, despite their significant flaws e.g. its low efficiency (Rewe, 2021) and high gas losses in the overflow tank. Therefore, there are higher emissions of greenhouse gases (such as carbon dioxide, methane, and nitrous oxide (Paolini, et al., 2018). These gas losses in the overflow tank can be seen with the naked eye as bubbles in the slurry. These gas losses can be captured (by the use of a cover for the overflow tank) to obtain a higher gas production with the same feedstock and also to reduce greenhouse emissions. The global efficiency of the installation can be further increased by placing a flexi biogas installation in series with the fixed-dome digester. In this way, the installation is also more suitable for educational purposes for the university. The flexi biogas installation ensures that the biomass undergoes a more complete digestion process. Other disadvantages of the fixed-dome digester are gas pressure fluctuations (which complicated the usage of the gas), possibly high gas pressure, no visualization of the gas content and the invisible development of cracks in the digester (that can cause gas leaks). The problems concerning gas storage can be solved by using the right type of external gasholder. In order to prevent the cracks, an experienced biogas technician is needed for the supervision of the construction (Bensah, 2009), (energypedia, 2016).

The main goal of this paper is in first place to design a hybrid biogas installation consisting of a fixed-dome and flexi biogas installation for the Technical University of Mombasa to increase gas production and reduce greenhouse emissions. The fixed-dome installation is the starting point for the design of the hybrid installation. In addition, it is intended to predict the gas production and the performance of the hybrid installation. (Deferme & Saulo, 2020).

Types of digesters

As mentioned before, the fixed-dome digester is the starting point for the hybrid plant and the calculations. An extensive motivation for the fixed-dome digester can be found in the master's thesis "Design and implementation of a hybrid biogas installation to reduce environmental pollution and food waste" (Corthouts & Vanhoudt, 2021). In this section, the different types of digesters are briefly discussed.

A *fixed-dome digester* has a fixed, permanent construction that consists of a closed dome-shaped digester with a fixed gasholder, an inlet tank and an overflow tank. A fixed-dome digester is characterized by a robust construction, a long lifespan and low efficiency (Charles, Jo, Henri, David, & Henry, 2011).

A *floating-drum digester* consists of a cylindrical digester and a movable, floating-drum gasholder. The floating-drum digester is less robust than the fixed-dome digester, has a similar efficiency, can deliver biogas at constant pressure and gives a visual indication of the amount of gas being stored (Charles, Jo, Henri, David, & Henry, 2011), (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014).

A *balloon-type digester* consists of an elongated, heat and weather resistant plastic or rubber bag, which serves as both a digester and gasholder. This digester is characterized by high efficiency and fragile construction. The flexi biogas installation is an innovative balloon-type digester (Charles, Jo, Henri, David, & Henry, 2011), (REWE), (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014).

A *hydraulic digester* consists of a concrete belly, a concrete neck and a gasholder made of a synthetic fiber material. The digester combines the advantages of the fixed-dome and the floating-drum digester, however with adding the complication that the entire digester is filled with water and the need for water storage pits (Asheal, Patrick, & Golden, 2017), (Charles, Jo, Henri, David, & Henry, 2011), (Edem & Abeeku, 2010), (PUXIN, sd).

Fixed-dome digester

In this chapter, the design of the fixed-dome digester will be discussed. The digester serves as a starting point for the calculations, which will be extended to a hybrid installation. The other calculations will be based on the calculations of the fixed-dome digester, which are extensively discussed in the master's thesis "Design and implementation of a hybrid biogas installation to reduce environmental pollution and food waste" (Corthouts & Vanhoudt, 2021). The design of the fixed-dome digester that will be used and evaluated is shown in Figure 1.

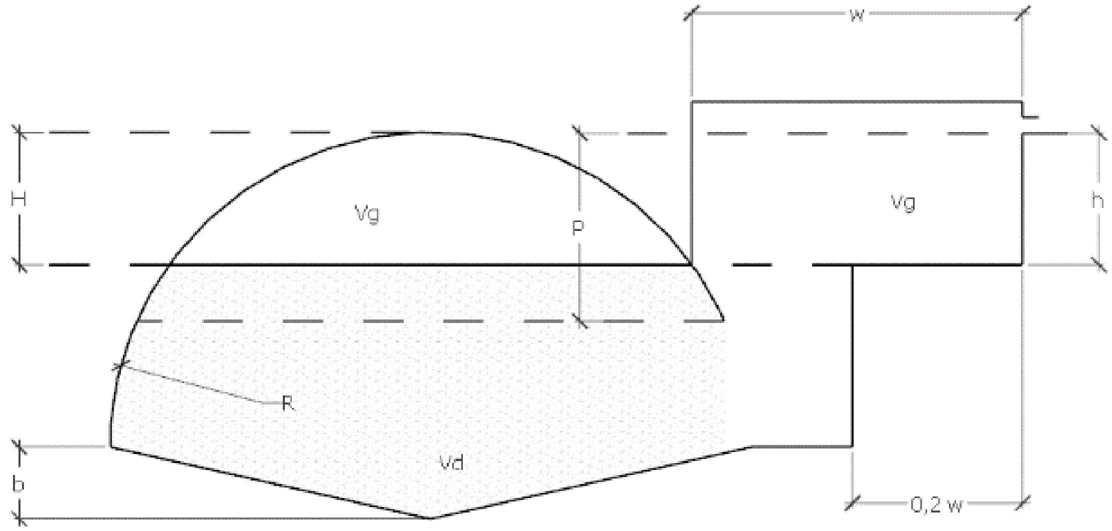

Figure 1: Design of fixed-dome digester (Bensah, 2009)

Calculations

The volume of the digester and has to be adjusted to the available amount of biomass. This volume is one of the factors determining the amount of gas produced. Another factor that determines the volume of the digester is the retention time of the biomass. This relationship is given in (1).

$$v = \frac{V_d}{R} \qquad (1)$$

v: daily feed rate (m³/day)
V_d: digester volume (m³)
R: slurry retention time (days)

The ideal retention time for a tropical climate with an average ambient temperature of 25–30 °C is recommended to be around 30 days (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014), (Edem & Abeeku, 2010) and can be confirmed in test set-ups (B., V., & S., 2015). In this temperature range, the digester operates at mesophilic temperature.

The next thing that has to be determined is the biomass to water ratio. In practice, the exact amount of water added to the food waste will not be measured. The mixture must be sufficiently watery to prevent clogging and to ensure a smooth flow. Therefore, a water ratio of about 1: 3 is usually applicable and is chosen for (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014), (Heegde, 2010), (RURA, 2012).

The water combined with the food waste forms a daily feedstock of 0.4 m³/day (as shown in equation (2)), using the approximation that 1 kg substrate is equivalent to 1 l (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014) and the given of 100 kg of food waste a day.

$$v = 100 + 3 \cdot 100$$

$$v = 300 \frac{l}{day} = 0.4 \frac{m^3}{day} \qquad (2)$$

Using the calculated feedstock and the retention time, the active digester volume can be calculated using (3).

$$V_d = v \cdot R \qquad (3)$$

$$V_d = 0.4 \cdot 30$$

$$V_d = 12{,}000\, l = 12\, m^3$$

Dimensioning

In order to size the digester, a digester/gasholder ratio and w:l ratio for the overflow tank must be chosen. A small digester/gasholder ratio of 1:8 (Corthouts & Vanhoudt, 2021) and a w:l ratio of 5:8 (Bensah, 2009) are chosen. The dimensions/ parameters of the digester (shown in Figure 1) are shown in Table 1.

Table 1: Relationships between the digester parameters for various ratio's (Ludwig, 1988, p. 51) and results of the equations.

V_g:V_d	*1:8*	
R	$\sqrt[3]{0.46\,V_D}$	*1.8 m*
H	$0.32R$	*0.58 m*
h	$0.28R$	*0.50 m*
P	$0.41R$	*0.74 m*
b	$0.25R$	*0.45 m*
w	$\sqrt{\frac{5}{8}\frac{V_G}{h}}$	*1.37 m*
l	$\frac{8}{5}w$	*2.19 m*

Estimation of biogas production

As mentioned earlier, 100 kg of food waste a day will be used as feedstock for the digester in TUM. The available biowaste is assumed to have a total solids (TS) of 10% on average. In other words, of the 100 kg wet weight (food waste) 10%, which is equal to 10 kg, is dry matter (Wellinger, Murphy, & Baxter, 2013). Of this 10 kg dry matter, 80% is volatile. So the amount of the volatile solids is 8 kg and the non-volatile amount is 2 kg. The rest of the biowaste is water and does not contain volatile solids. So it can be concluded that of the 400 kg of feedstock (100 kg food waste + 300 kg water) the volatile solids (VS) is 8 kg. Using the approximation that 1 kg substrate is equivalent to 1 liter, 1,000 liters of biomass would contain 20 kg VS (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014).

First, the organic loading rate (OLR) is calculated in (4). An OLR below 2 kg VS/m^{3}day is considered ideal (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014).

$$OLR = Q \cdot \frac{S}{V_D} \tag{4}$$

$$OLR = 0.4\frac{m^3}{day} \cdot \frac{20\ \frac{kg\ VS}{m^3}}{12\ m^3}$$
$$OLR = 0.67\ \frac{kg\ VS}{m^3\ day}$$

Q: substrate flow rate (m^3/day)
S: substrate concentration inflow (kg VS /m^3)
V_D: active reactor volume

The next step is to calculate the biogas and methane yield. Fruit/vegetable/food waste usually produces biogas quantities of 0.60-0.70 m^3/kg VS with the assumption of 0.4 m^3 CH_4 / kg VS and a methane (CH_4) content of 65% (Kuo & Dow, 2017), (Tabatabaei & Ghanavati, 2018), (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014). Because the band of 0.60-0.70 is still wide, the average of literature recommended methane yield and a calculated methane yield will be used.

Using a first order kinetic model, the methane production can be calculated. The methane and biogas production for food waste is given by equation (5) (Wellinger, Murphy, & Baxter, 2013). In order to get the biogas and methane production, the retention time must be given as the time in equation (6).

$$Y(t)_{methane} = \tag{5}$$
$$Y_{max}[1 - 0.88 \cdot e^{1.02 \cdot t} - (1 - 0.88)e^{-0.06 \cdot t}]$$

$$Y(30)_{biogas} = \frac{Y(30)_{methane}}{65\%} \tag{6}$$
$$= 0.71\frac{m^3 biogas}{kg\ VS}$$

$Y_{methane}$: methane yield $(m^3 CH_4/kg\ VS)$
Y_{biogas}: biogas yield $(m^3 biogas/kg\ VS)$
t: time (days)

Table 2 summarizes the biogas yield. The average value of 0.66 $\frac{m^3 biogas}{kg\ VS}$ is used.

Table 2: Biogasyield from different sources

Biogas yield $\left(\frac{m^3 biogas}{kg\ VS}\right)$	**Source**
0.71	equation (6) (Wellinger, Murphy, & Baxter, 2013)
0.61	(Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014)
0.66	Average

The daily biogas production of the fixed-dome installation is calculated in (7), with the assumption of an average methane (CH_4) content of 65% (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014):

$$Q_{biogas} = Y_b \cdot VS = 0.66 \frac{\mathrm{m}^3}{\mathrm{kg}} \cdot 8 \frac{kg}{day} = 5.28\ m^3\ /\mathrm{day} \quad (7)$$

Q_{biogas}*: biogas production per day (m³/day)*
Y_b*: biogas yield (m³/ kg VS)*
VS*: volatile solids per day (kg/day)*

Disadvantages of a fixed-dome digester

The main purpose of the hybrid installation is to largely eliminate the disadvantages of the fixed-dome installation and to increase efficiency. The main problem of the fixed-dome digester in practice is its low efficiency. Other disadvantages are gas pressure fluctuations (which complicated the usage of the gas), possibly high gas pressure, no visualization of the gas content and the invisible development of cracks in the digester (that can cause gas leaks). These problems concerning gas storage will be tackled by the use of an external gasholder. This is discussed in the chapter "Gasholder" and the problem concerning cracks can be prevented when an experienced biogas technician is helping with the supervision of the construction (Bensah, 2009), (energypedia, 2016). Also, the digestion temperatures are on the low side, resulting in low gas production and thus lower efficiency.

The slurry coming out of the plant has undergone a relatively incomplete digestion process. In other words, this slurry still has potential for gas production. As a result, gas production still takes place in the overflow tank and in the digestate storage tank. This biogas is not collected and can therefore be seen as a loss, but also as great potential for a higher efficiency.

Gas losses

As mentioned earlier, a lot of gas losses occur in a fixed-dome digester which results in a low overall efficiency. At the moment, very little research has been done on these gas losses. A test set-up, that consisted of a temporary transformed fixed-dome digester in Nairobi showed that only 31.4% of the total gas production is captured in a normal fixed-dome digester. From the total gas production 32.1% is lost in the overflow tank and 36.5% is lost in the digestate storage (Flexi Biogas Solutions, 2020). However, there is too little research and literature on the gas losses to indicate the losses with one fixed percentage, but these results give a good indication of the losses and look very promising for the potential of a hybrid system.

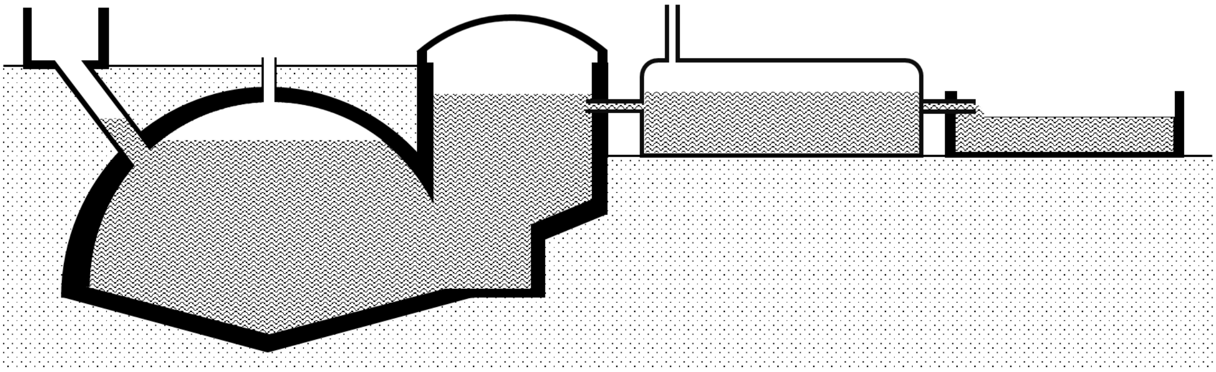

Figure 2: Hybrid biogas installation

The mentioned percentages only take the actual gas flow into account. However, some properties and parameters of the digestate differ from the fresh feedstock (Murphy, Braun, Weiland, & Wellinger, 2011), (Wellinger, Murphy, & Baxter, 2013), and therefore the energetic value and the methane content of the gas produced from the overflow tank can be lower from the gas produced from the fixed-dome digester.

Hybrid biogas installation

In this section, the motivation for the hybrid biogas installation and its design are discussed together with the total expected gas production. The hybrid installation will consist of a covered overflow tank and a flexy biogas installation placed in series with the fixed-dome digester as shown in Figure 2.

Benefits of covering the overflow tank

The first problem that will be tackled is the gas losses in the overflow tank. This problem can easily be solved by covering the overflow tank. Covering the overflow tank has several advantages. During the hydraulic working of the digester, a lot of fresh biomass will be pushed into the overflow tank, due to the up and down movement of the biomass due to gas production and gas withdrawal (Charles, Jo, Henri, David, & Henry, 2011). Because of the fresh biomass in the overflow tank, there will be a lot of gas production, this produced gas will be released into the atmosphere and thus releasing greenhouse gasses in the atmosphere and losing valuable biogas. Therefore, the main two benefits of covering the overflow tank are capturing biogas and reducing greenhouse emissions. An additional benefit is preventing the escape of odors (Murphy, Braun, Weiland, & Wellinger, 2011).

Flexi biogas installation

The efficiency can be further increased by placing another biogas installation in series with the fixed-dome installation. In this way, the installation is also more suitable for educational purposes for the university. The flexi biogas installation has a high efficiency and is characterized by a complete digestion process. The flexi biogas installation is one of the most common new biogas installations in Kenya. This installation can be purchased prefabricated at a low cost compared to other biogas technologies. Since the flexi biogas installation and the fixed-dome digester are common in Kenya, it is interesting to show the potential of combining these technologies. In addition, the flexi biogas installation solves some disadvantages of the fixed-dome plant: the low efficiency and the incomplete digestion process.

The flexi biogas installation consists out of three main parts: the balloon, the UV filter and the net. *The balloon* is the digester itself and also functions as a gasholder. It can also be seen as a bag that can be opened via a lip. The lip is a zip-like seal and is present at both ends of the balloon. The digester can easily be emptied true these lips. *The UV filter* (the greenhouse fabric) protects the balloon against UV radiation in order to expand its lifespan. *The net* offers protection against mechanical damage like puncture. The net and the UV filter form the tunnel, the tunnel helps to keep the temperature high (around 40°C for the climate in Mombasa) which is near-optimal temperature. The tunnel captures heat during the day and therefore increases the temperature of the substrate inside the balloon and during the night the tunnel acts as an isolation jacket to prevent heat losses. By keeping the temperature high, gas production is kept high. The greenhouse tunnel has to be replaced approximately every 5 years (IFAD, 2014).

Design of the hybrid installation

The design of the hybrid biogas installation is shown in Figure 2. The cover over the overflow tank captures the gas released and produced in the overflow tank. Because the overflow tank is covered, the digester can't be accessed through the overflow tank. Therefore, a zip-like seal opening has to be added to the balloon that covers the overflow tank. The flexi biogas installation increases the total digester volume and thus increasing the overall retention time which implies more gas production. In the hybrid installation the later digesting phases (taking place in the flexi biogas installation) are separated from the earlier digesting phases (taking place in the fixed-dome digester). Therefore, a more complete digesting process can be expected in comparison with the fixed-dome digester. The slurry fed to the flexi biogas installation consists out of a mixture of different digesting phases. Thus it can be expected that the flexi biogas installation is not as efficient as a standalone flexi biogas installation. Because the installation has never been built before, the efficiency and the impact of the added parts in comparison with a stand-alone fixed-dome digester are unknown.

Total gas production of the hybrid biogas installation

In the section Gas losses, the results of a similar hybrid system are discussed. This test installation shows that approximately an equal gas flow as in the fixed-dome installation was obtained from the overflow tank. However, there is no literature to back this up. The assumption that a covered overflow tank can double the output of the fixed-dome digester is optimistic. Because a lot of fresh biomass will occur in the overflow tank, the overflow tank has a big potential for extra gas production. An added gas production of 75% obtained from the covered overflow tank is assumed.

The output of the overflow tank is already partially digested. Therefore, the input for the flexi biogas installation has a lower potential for gas production than the food waste. Because of this, a gas production equal to 50% of the gas production of the fixed-dome installation is assumed. In total, gas production is assumed to be 2.25 times that of the fixed dome plant, giving Q=11.88 m³/day.

Simulation

This section discusses the calculations and a simulation in order to estimate biogas production and consumption. This simulation will be done based on the consumption pattern and the expected production to determine the peak gas content of the gasholder. The size of the gasholder will be based on the results of the simulation. The volume of the gasholder depends on four parameters: the daily gas production, the time when the tap from the digester to the gasholder is opened, the amount and time when biogas is used.

Consumption pattern

In order to determine the volume of the gas storage, the gas consumption must be known and the moments of gas consumption. Existing installations show that 40-60% of the daily biogas production has to be stored (Ludwig, 1988), (Thomas, et al., 1999). According to these estimations, the volume of the gasholder should approximately be 4.8-7.1 m³. However, the needed amount can differ a lot from these values depending on the consumption pattern.

The kitchen which will be provided with biogas uses firewood and charcoal. In order to use the current consumption of firewood and charcoal, the biogas equivalent must be determined. The firewood and charcoal biogas equivalent is calculated in equations (8) and (9).

$$V_{firewood} = NCV_{fw} \cdot \frac{\eta_{fw}}{\eta_{bg} \cdot NCV_{bg}} \tag{8}$$

$$= 14.7 \cdot \frac{0.24}{0.55 \cdot 23.27}$$

$$= 0.276 \frac{m^3}{kg\ firewood}$$

$V_{firewood}$: *m³ biogas/kg firewood*

NCV_{fw}: *net calorific value of firewood 14.7 MJ/kg*

NCV_{bg}: *net calorific value of biogas: 23.27 MJ/kg*

η_{fw}: *efficiency of the firewood stove: 24%*

η_{biogas}: *efficiency of the biogas stove: 55%*

$$V_{charcoal} = NCV_{cc} \cdot \frac{\eta_{cc}}{\eta_{bg} \cdot NCV_{bg}} \tag{9}$$

$$= 28.4 \cdot \frac{0.30}{0.55 \cdot 23.27}$$

$$= 0.666 \frac{m^3}{kg\ charcoal}$$

Table 3: Consumption overview of a week day

Duration	Firewood [kg]	Charcoal [kg]	Biogas equivalent [m³]	Water temp. [°C]
2:30	67.5	0	18.63	47
0:30	19.5	0	5.38	46
1:00	21.6	21	19.95	45
1:00	0	10.5	6.99	45

$V_{charcoal}$: *m^3 biogas/kg charcoal*
NCV_{ch}: *net calorific value of charcoal: 28.4 MJ/kg*
$\eta_{charcoal}$: *efficiency of the charcoal stove: 30%*

The calculations conclude that 1kg of firewood is equivalent to 0.276 m^3 of biogas or 1 m^3 of biogas is equivalent to 3.63 kg of firewood. For charcoal is 1kg equivalent to 0.666 m^3 of biogas or 1 m^3 of biogas is equivalent to 1.50 kg of charcoal. An overview of the consumption pattern is shown in Table 3. However, there needs to be noted that on Saturday, the daily gas consumption is just 20% of the gas consumption during the weekdays and on Sunday only 10%. This must be taken into account when determining the volume of gas storage.

Gas tap regulation

In a standard fixed-dome digester, fresh biomass regularly enters the overflow tank. This happens when fresh biomass is brought into the digester, which will also be the case with the hybrid installation with an external gasholder. Each time when gas is consumed or produced, the gas pressure in the fixed-dome digester changes, causing slurry to flow in or out of the overflow tank. This movement of the slurry prevents the formation of a scum layer. A scum layer can hinder gas production. Because an external gasholder will be used that guarantees a constant gas pressure in the digester (see section ‘Gasholder’), this constant movement of the slurry does not take place because the gas pressure stays nearly the same. For this reason, it is necessary that the piping from the fixed-dome digester to the external gasholder is closed at certain times. In this way, there is a movement of the slurry at the times when the tap is closed and when the tap is opened. When closing or opening the tap, the pressure in the digester will suddenly drop to approximately the pressure of the external gasholder, causing a sudden movement of the slurry. In this way, the formation of a scum layer is prevented.

For the installation at TUM, the tap will be opened at 3:15 and closed at 13:30 (the tap is opened when the first staff arrives and closed when the kitchen is about to close). This means the tap is opened for approximately 10 hours and closed for 14 hours. When the tap is opened at 3:15, all the gas production from the time when the tap is closed will flow to the gasholder. This results in a maximum gas content in the gasholder.

Results of the simulation

The simulation is done in Python. The gas content for the gasholder in function of time for two weeks is shown in Figure 3. This figure shows that the gas consumption during the week is higher than the gas production. However, during the weekend the consumption is lower than the gas production. Therefore, the gas content is repetitive on weekdays and increases over the weekend. The maximum gas content of 15.1 m^3 is achieved on Monday morning when the gas tap is opened. During weekdays (except Monday morning) a maximum gas content of 7.7 m^3 is achieved and on Monday morning a maximum gas content of 15.1 m^3 is achieved.

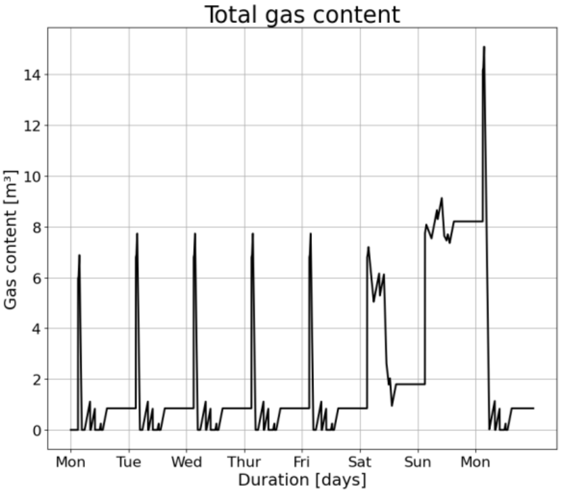

Figure 3: Gas content of the gasholder(s) in function of time for 2 weeks

Note that these volumes are for standard conditions (25°c and 1 bar). The actual temperature and pressure will both be higher, approximately compensating for each other, but these do not differ much from the standard conditions.

Gasholder

This section discusses the design and calculating of the gasholder. The results of the simulation discussed in the section ‘Simulation’ are used in order to dimension the gasholder. The gas storage present in the hybrid installation will be taking into account when determining the size of the external gasholder.

Design of the gasholder

The gasholder must succeed in eliminating the following disadvantages of the fixed-dome installation: gas pressure fluctuations, possible high gas pressure and the invisibility of the gas content in the digester. Another important function of the gasholder is to capture the gas peaks in order to fully utilize the biogas production. All the mentioned disadvantages can be eliminated by using a floating-drum gasholder, shown in Figure 4.

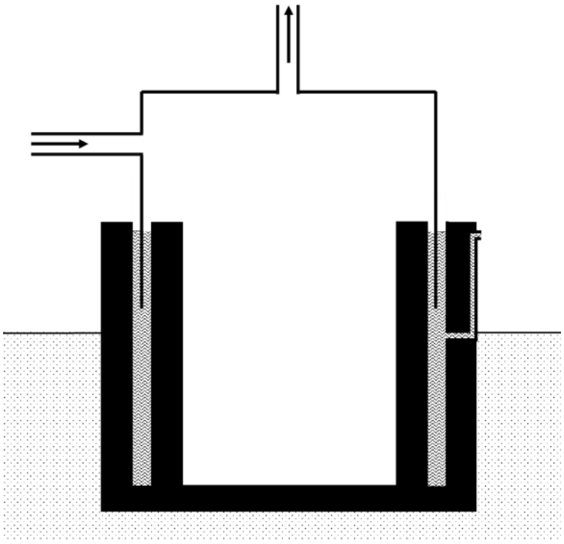

Figure 4: Schematic representation of the floating-drum gasholder

The drum floats on the water. The produced biogas collects in the gas drum and pushes the drum upwards. This gas drum can rise or fall depending on gas production and gas consumption. The level of the drum is thus a visual indication of the available quantity of biogas. Constant gas pressure can be guaranteed by the rise and fall of the drum. The weight of the drum applies pressure to the gas in the drum. This creates a certain gas pressure that is approximately constant, regardless of the amount of gas in the drum. If higher gas pressure is required, the higher pressure can be obtained by placing additional weights on the drum. With this type of gasholder, a safety valve is not necessary. If the drum becomes too full, the excess gas can escape because the edge of the drum is briefly above the water (Vögeli, Riu Lohri, Gallardo, Diener, & Zurbrügg, 2014). More details on the design of the gasholder and the materials used can be found in the master's thesis "Design and implementation of a hybrid biogas installation to reduce environmental pollution and food waste" (Corthouts & Vanhoudt, 2021).

Determining the gasholder volume

As mentioned in the section “Results of the simulation” the peak gas content is 15.1 m³. In order to determine the size of the external gasholder, there need to be looked at the size of the gas storages present in the total hybrid installation. These gas storages are present in the fixed-dome digester, the covered overflow tank and in the flexi biogas installation. These have a combined gas storage capacity of 7.5 m³. This means that a minimum of 7.6 m³ has to be stored inside the external gasholder. When taking into account a 20% safety margin (total gas storage of 18 m³) 10.4 m³ has to be stored inside the external gasholder.

Conclusion

The total installation consists of three parts: the fixed-dome digester, the extensions leading to a hybrid installation and the external gasholder. The installation initially starts from a fixed-dome digester. This has been further expanded into a hybrid installation to solve problems of the fixed-dome digester such as low efficiency. The hybrid installation in total consists of a fixed-dome installation with a covered overflow tank, a flexi biogas installation and a floating-drum gasholder.

The most important inputs that determine the size of the digester are the daily available food waste (100 kg), the retention time (± 30 days) and the biomass/water ratio (± 1:3). From these inputs, it can be concluded that the active volume of the fixed-dome digester is 12 m³. Daily gas production of 5.28 m³ can be expected for the designed fixed-dome digester with kitchen waste as feedstock. For the designed hybrid system, on the other hand, a daily biogas production of 11.88 m³ can be expected. To determine the size of the gas storage, a simulation was performed that takes into account the consumption pattern and the daily gas production. This simulation concludes that the peak gas volume that needs to be stored is 15.1 m³. Taking into account the volume of gas that can be stored in the fixed-dome, covered overflow tank and the flexi biogas installation, the external gasholder should be able to store 10.4 m³ of gas, taking into account a safety margin of 20%.

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