Performance of domestic biodigesters in Kenya

Towards the development of a comparative method for measuring the performance of different biodigester types in Sub-Saharan Africa

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Picture from personal archieve

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ABPP
Biogas Cleaner Energy
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Executive summary

To eradicate (extreme) poverty, the Sustainable Development Goals (SGDs) framework has been set by the *United Nations* (UN). Providing access to clean energy resources to populations of the *least developed countries* (LDCs) is considered crucial. For a number of decades, domestic biogas has been introduced as a promising technology, providing multiple benefits in the context of sustainable development. Through daily feeding of cow dung, a biodigester provides clean cooking and a nutrient rich digestate that is usable as a high-quality fertilizer. *Africa Biogas Programme Partnership* (ABPP) was set up by Dutch development organisations to help develop a biogas market in five countries in Sub-Saharan Africa. Growth of the biogas leads to a diversification of the available biodigesters. However, the biodigester selection process is still based on applying single-standards for large regions, due to a lack of practical knowledge on biodigester performance. This research was conducted to develop a performance measuring method suitable for obtaining comparative and scientifically robust results for multiple digester types.

By considering a techno-operational and financial performance definition, a profile containing was set, including eight *performance indicators*: gas production per unit of dung input, gas pressure, stability of gas production under feeding and temperature instability, gas storage volume, investment costs, ease of use, robustness, and surface requirements. The usability of five *measuring tools* (biodigester database, user survey, logbook, data logger, visual observation) was assessed during four performance measuring pilot studies in Kenya and Uganda. Scores were given both for the *use process* of the tool and the *quality of the data* that is generates. In addition, the availability of potentially improved measuring tools was researched. Pilot results show that the database is easy to use but does not deliver high-quality data. The survey and visual observation have reasonable process scores. The survey is slightly recommended for measuring investment costs and ease of use, while visual observation measures surface requirements and can be used occasionally for other indicators. The logbook scored intermediate for the process, but is nevertheless the best tool for measuring dung input, although standardization of dung input for every biodigester is an alternative. The data logger is a complex, expensive and complex tool to use, putting the process of successful data collection at risk. However, the tool seems to be essential for monitoring most technical parameters. Developing a second-generation data logger with updated technology would have many benefits in comparison to the initial data logger for the process of using the tool and the quality of the generated data. The required investment for the development of this tool is expected to be profitable after a couple of field studies, taking into account the savings on logistics.

A first fundamental step towards a performance measuring method is described. A method based on surveys, visual observations and a second generation data logger is suitable for explaining seven of the described performance indicators. A measuring tool that can monitor the robustness of multiple digester types is yet to be found. For a number of indicators, concrete measures of expressing the performance are required - a recommendation for further research. Furthermore, a review of the quality of various flow meter types should be done before developing a new data logger. Future experiences with performance measuring, in accord with this framework, could lead to revision of the selection of measuring tools or widening of the performance profile, including economic, environmental and business-quality related indicators.

Abbreviations

ABPP	Africa Biogas Programme
AD	Anaerobe Digesting
BCE	Biogas Construction Enterprise
BY	Biogas Yield
DGIS	Directorate General for International Cooperation of Dutch Ministry of Foreign Affairs
DM	Dry Matter
GPRS	General Packet Radio Service (type of mobile data connection)
HDI	Human Development Index
Hivos	Humanistic Institute for Development Cooperation
IEA	International Energy Agency
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
KBP	Kenya Biogas Program
LDCs	Least Developed Countries
LPG	Liquid Propane Gas
LSL	Lower Slurry Level
MDGs	Millennium Development Goal
MT	Measuring Tool
oDM	Organic Dry Matter
PI	Performance Indicator
RQ	(main) Research question
SDGs	Sustainable Development Goals
SQ	Sub question of the main research question
SNV	SNV Netherlands Development Organization
UN	United Nations
SSA	Sub-Saharan Africa
VOCs	volatile organic compounds

Contents

1 Introduction

In the modern world reduction of extreme poverty is widely considered as one of the major challenges for human society. Over the last decades, hundreds of millions of people have been able to escape extreme poverty: between 2002 and 2012 the proportion of the world wide population living below the poverty line dropped from 26% to 13% [1]. However, there are still 800 million people living in extreme poverty [1]. In 2012, 40% of the Sub-Saharan African (SSA) population lived from a daily income of less than $1.90 [1]. Nevertheless, the majority of worldwide population growth occurs in the least developed and most vulnerable parts of developing societies.

In the year 2000, the *Millennium Development Goals* (MDGs) were set by the United Nations (UN) to inspire the development of the least developed parts of the world [2], which was followed up by the *Sustainable Development Goals* (SDGs) set in the *2030 Agenda for Sustainable Development* [1]. The SDGs goals are formulated in an interdisciplinary context, that integrally aim for eradicating (extreme) poverty with a balance between the economic, social and environmental dimensions. The SGDs cover multiple themes, such as health, environment, gender equality and sustainable growth [1], Hence, the development of the poorest countries is a problem that should be solved using broad and interdisciplinary frameworks.

1.1 Energy poverty

Lack of energy resources is considered as one of the fundamental causes of extreme poverty [1,3,4], a relationship that is described as *energy poverty*. In a special report on energy poverty the International Energy Agency (IEA) states that around 36 billion dollars of annual investments are required by 2030 in order to create global energy access [4]. They warn that ''unless new and dedicated policies are put into place, conditions for the lives of billions of people are not expected to improve'', putting energy in a central position for fulfilling the SDGs.

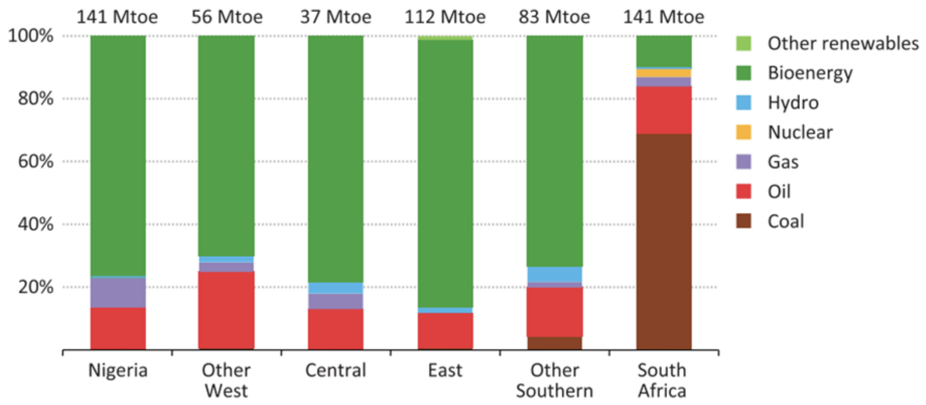

Figure 1: The Primary energy mix of Sub-Saharan Africa, divided by sub-region, that is highly dominated by bioenergy, mostly from traditional sources. Source: [5].

The Human Development Index (HDI) shows that the majority of the low developed countries are located in Sub-Saharan Africa (SSA) [6]. Generally, most of the residential energy demand of the region is for cooking purposes [5]. Around 80% of the region's population relies on traditional solid biomass. This energy demand is likely to grow by 40% towards 2040 [5]. As shown by Figure 1, the primary energy consumption is highly dominated by bioenergy, which mainly includes wood based fuels.

Clean cooking has many serious benefits [4], including reduction of exposure to air pollution, time savings and financial benefits, in particular to women who are usually responsible for cooking in most of the regions cultures. Additionally, clean fuels can significantly reduce the local ecological footprint. These benefits underline why the International Energy Agency mentions energy access as essential for eradicating extreme poverty and sustainable development according to the SDGs.

1.2 Domestic biogas production

During the last decades, biogas production has emerged as a promising solution for clean and sustainable cooking in of developing countries [7], especially in rural regions. The technology is based anaerobic digestion (AD) by microbes that produce biogas by degrading a diluted mixture of animal manure and other biodegradable substances [8], which takes place in so-called domestic biodigesters. The biogas is a clean cooking fuel and the fluid residue (bioslurry) can be used for multiple fertilization purposes. It is a reliable and low-threshold technology for applying in low-developed rural areas, contributing to at least 5 SDGs [9] (appendix 8.1.2).

The emerging of domestic biodigesters in developing countries has led to innovation [10]. Multiple digester types (appendix 8.2.3) have been designed, of which the brick-dome type is the most widely spread. Recently, many pre-fabricated digesters have entered the market. All types have product-specific strengths and weaknesses, although the potential of a certain type depends on many factors.

The dissemination has been proved successful outside Africa since the seventies [7]. The installations of domestic biodigester in the SSA region has been less successful, although the economic potential is estimated on two million biodigesters [9]. The African Biogas Partnership Programme (ABPP) was set up in 2008 and aims create a domestic biogas market in five countries in the region, aiming on 100,000 installations in the second phase of the program [10] (see appendix 8.1.3).

1.3 Problem definition

Although progress has been made, the uptake of biogas technology has been disappointing in certain areas. A recent study in Uganda showed, for instance, that just a quarter of the installation potential has been reached [11], despite ABPP activities. Another unfortunate phenomenon is the high frequency of dis-adoption of digesters, within a few years after commissioning [11], up to 80%. Disappointing performances of existing plants result in early dis-adoption of plants and a negative image of the technology [12].

Disappointing performance is the consequence of fact that the installed digester types often do not match the conditions of the household [11]. This (mis)match is usually described by *fit*, as visualized in Figure 2. This is mostly the result of applying single standards for large regions [13], instead of finding the best fit. Also, existing biodigester models rather focus on theoretical perceptions and have not been falsified sufficiently. Another problem is that the product information of new biodigesters that enter the market describe unrealistic performances, sometimes exceeding theoretical limits [14]. Performance measuring can solve these problems via different routes in the ABPP organization (appendix 8.1.4).

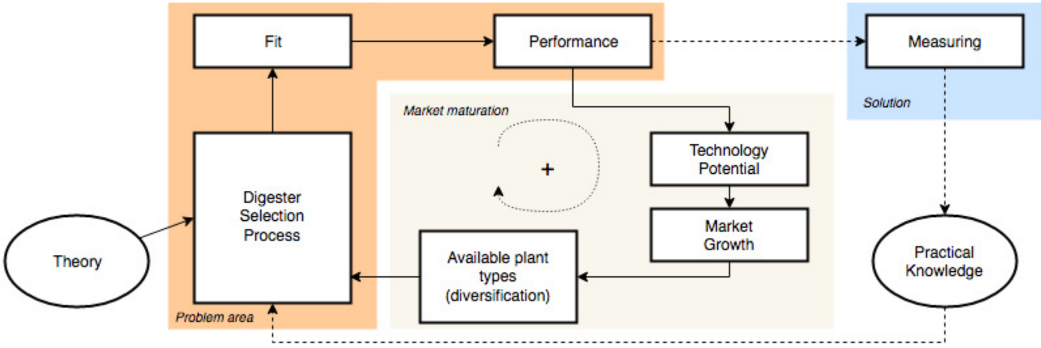

Figure 2: visualization of the defined problem and performance measuring as potential solution. The process of market maturation in is also visualized. Figure from personal archieve, based on: [13 10].

To get clear overviews of digester performance, efforts have been made to measure and compare the performance of digester types. A data logger was developed in 2014 for performance measuring. In 2015 a performance measuring study was performed in Rwanda to compare the performance of three digester types [14–16]. Another study in Tanzania was done to compare the performance of two different designs of the common brick-dome type [13,17].

Both studies seemed to be focused too much on conclusions in the short term [13,16] and did not seem to focus on improving the experiences and methods of performance measuring for ABPP and its partners. Since then, no attempts have been made due to a lack of priority and finances. So far, no reliable method has been developed to obtain practice knowledge for the falsification of this information and there are not clear enough standards for biogas performances [11].

1.4 Research question

With the assignment for this study ABPP aims to develop a first protocol for domestic biogas performance measuring [13,14,18]. Use of the method in the field can lead to improvements. It is important that the proposed method is simple enough to be used by local biogas technicians [14], that the obtained data is based on the same methods and standards as measuring studies in other regions [18](comparativeness), and that academically reliable conclusions can be drawn [13]. This leads to the main research question:

How can a comparative method be developed that is suitable for mapping the performances of domestic biodigesters in Sub-Saharan Africa?

In order to answer the main research question, three sub questions will be answered:

1. How is the performance for domestic biogas production defined (a) and which indicators determine the performance of a domestic biodigester significantly (b)?
2. Which measuring tools for these indicators are available (a) and are suitable for mapping the performances of biodigester types (b)?
3. Which selection of measuring tools is the most promising for setting up a uniform performance mapping method?

2 Theoretical background

To determine how the performance of domestic biodigesters can be assessed, the understanding of certain concepts is required. First of all, basic understanding of the biochemical process (section 2.1) and the factors that enhance the process is required. Secondly, the application of this process in useful technology for domestic use (section 2.2) is explained. Finally, the concept of performance is defined (section 2.3) on the basis of reviewing the reports of previous reports related to biodigester performance.

2.1 Biogas production by anaerobic digestion

Domestic biodigester types operate by wet fermentation of organic substrates. Anaerobic digestion (AD), which takes place in absence of oxygen, is the bio-chemical process that is responsible for the fermentation [8]. During the AD process biogas is produced. The liquid digestate is a secondary product that is usually named as bioslurry [19].

2.1.1 Chemical process

Biogas formation by the AD process consist of a number of linked processes, which are visualized in Figure 3 and further explained in appendix 8.2.1. Hydrolysis is the first phase, in which hydrolytic microorganisms split larger molecules into smaller fractions to become accessible for other microorganisms [8]. During acidogenesis and acetogenesis molecules are transformed into methanogenic substances, which can be used by methanogenic microorganisms for methane production (methanogenesis). In domestic biodigesters the four processes run parallel [8].

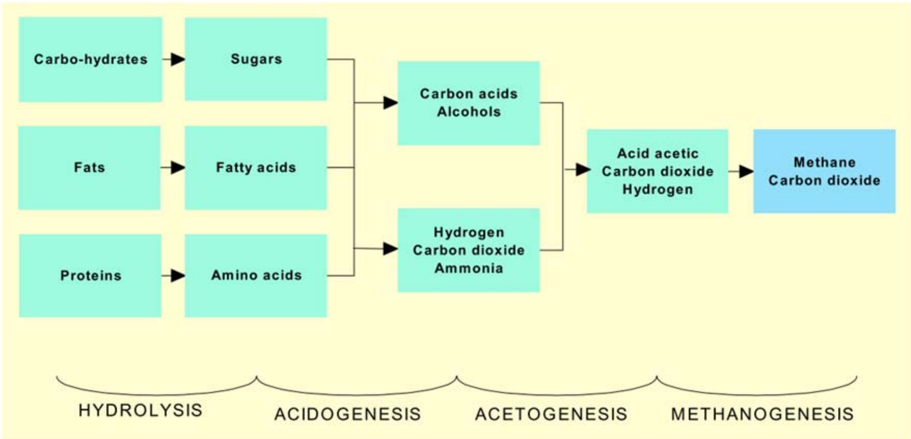

Figure 3: schematic visualisation of the four steps of the AD process. Source: [8].

Methanogenesis and hydrolysis are processes that are mainly important for well-performing domestic biogas technology. The hydrolysis step requires sufficient amounts of water to be mixed with the organic substrate. The performance of the methanogenesis step is mainly influenced by the absolute temperature of the substrate, temperature fluctuations, the stability and quality of feeding [8]. There are three temperature ranges in which the AD process can take place [8], of which the mesophilic temperature range is the most relevant for domestic biogas production. Higher temperatures generally accelerate the process because of a higher activity of microorganisms and temperatures below around 15 °C slow down or obstruct the process. Also, temperature fluctuations can inhibit the growth of microorganisms. It is therefore important that the temperature of the digestate remains both stable and warm [8 13].

2.1.2 Feedstock

The substrate for biodigesters is formed by a constant feeding of biodegradable non-fibrous materials. Animal manure is mostly used as main feedstock [20]. Also, other types of animal manure can be used. Some domestic biodigesters are connected to toilet of a household, since the majority of the pathogens is inactivated [21]. Also crop residues, fruits and kitchen waste are used as feedstock to the biodigesters.

The maximum volume of biogas that can be produced from a unit of mass of a certain substrate is called the biogas yield (BY) [22]. Feedstock containing a lot of sugars and fatty acids has a relatively high BY. Only the *dry matter* (DM), or the *organic part of the dry matter* (oDM), are determining for the BY. Therefore, the yield can be measured per kg of fresh matter ($BY_{fm,i}$) or per kg of oDM. Note that the BY is a theoretical quantity and the process also depends on other factors such as the pH and nutrient balance [23]. The gas production therefore depends on the total combination of components that are fed into the biodigester and the actual gas production is too complex for only relating to the BY of the feedstock.

Dung types usually have a low BY [20], because they have a high moisture content and a low oDM. Also, the majority of the energy has already been digested by the animal. Although the biogas yield of cow dung is among the lowest of all feedstocks (appendix 8.2.2), its availability is usually determining for the potential of the technology. Most digester owners own cows and the possession of a few cows delivers a household a reliable and large enough amount of feedstock every day. Furthermore, cow dung naturally contains a high concentration of the microorganisms that are required for the AD process.

Before feeding the dung is mixed with water to enhance the hydrolysis process in the substrate. When not enough water is added, the hydrolysis is obstructed and the gas production decreases. Also, the internal substrate can become too solid and obstruct the flow of substrate. A too high water-dung ratio lowers the BY per digester volume and inhibits the speed of the process. For some digester types water scarcity can be an obstacle for the technology. The biodigesters are usually advised to mix water and dung based on a ratio of 1:1 [23 24]. Furthermore, it is important for a stable AD process is that the digester is fed as continuously as possible [8], preferably on daily basis with equal quantities

2.1.3 Products

Biogas is the main product produced by biodigesters. For domestic biodigesters the gas has a methane content of usually between 50% and 60% of the volume and a heating value of 21 MJ per cubic meter [8] under atmospheric pressure (Nm^3), based on a methane content of 50%. The methane content of the biogas depends mainly on the type of input. A digester fed with cow dung generally has lower methane concentration than with a feedstock of pig or poultry dung [23]. It is not likely that the type of digester is determining for the methane concentrations. Biogas contains a large fraction of CO2, which is the second most abundant substance of the gas.

Biogas contains a fraction of the highly corrosive gas hydrogen sulphide (H_2S). Budget desulfurizers are available [25], containing iron oxide-containing pellets [26], which oxidize the H_2S to metallic sulphite or elemental sulphur. Further biogas properties are given in appendix 8.2.2.

The liquid digestate, bioslurry, is a secondary product. It is used as fertilizer, by direct application or after composting with other organic waste [27]. The AD process increases the C:N ratio of the substance and enhances the nutrient availability of the substrate for plants [27]. Bioslurry has proved to be a powerful organic fertilizer that replaces chemical fertilizers and increases the agricultural yield for many crops.

2.2 Domestic biodigesters

To apply the AD process for domestic purposes the process takes place in a domestic biodigester, which is an anaerobic reservoir under stable conditions, in which also a certain amount of gas can be stored. Domestic biodigesters are generally installed small-scale farmer households with sufficient space and livestock or another continues source of digester feedstock. Sometimes digesters are installed to process toilet waste [9] of e.g. schools or food waste [15] of restaurants.

2.2.1 Compartments

The main component of a domestic biodigester system is the anaerobic digester tank, which includes the *gas storage volume* and *digester volume* containing the substrate (Figure 4). In an inlet tub dung and water is mixed and fed to the bottom of the digester via an inlet connection. At the opposite side there is a connection that leads to an expansion chamber or output. The expansion chamber is located higher than the digester volume, therefore operating as a compensiation volume that maintains a pressure on the gas storage volume [28]. When the compensation volume level rises to a certain level it flows over and is irrigated to slurry pits or a drain. Note that the presence of oxygen in the expansion chamber stops the AD process by eliminating the anaerobic microorganisms. The produced gas is led to the stoves in the kitchen via a connection of pipes, which is regulated by both a main valve and a kitchen valve.

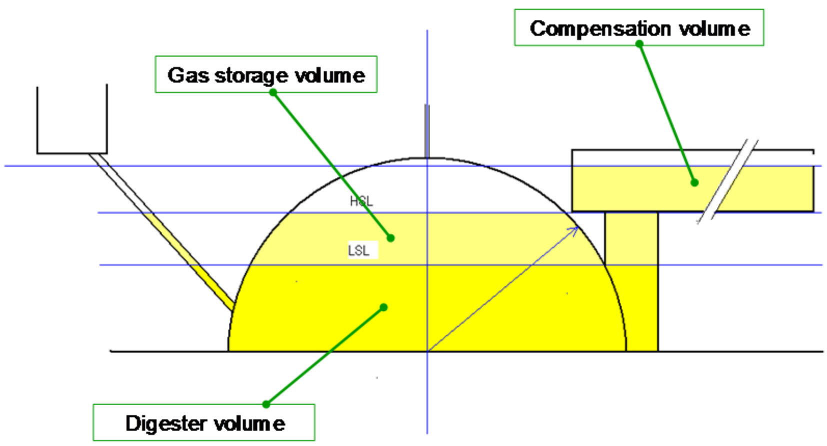

Figure 4: schematic visualization of the mixing tub (left), digester (middle) and expansion chamber (right) and the corresponding volumes. Note that this figure is based on the design of a brick dome digester type [28].

2.2.2 Retention time

The *hydraulic retention time* (HRT) of a biodigester is an important parameter that determines the rate of gas production. It is the time that the substrate volume on average needs to pass to the digester, and is hence related to the ratio between the total daily feeding and the volume of the digester [8]:

$HRT = Vr / V$ where Vr is the digester volume and V is the volume of wet substrate fed per day.

Using a suitable retention time is important for the quality of the process. With long retention times, more gas can be produced out of a unit of input in total, but the rate of gas produced per time unit is lower. When the retention time is too short it washes out the methanogenic microorganisms [22], which inhibits the AD process. ABPP advises to apply retention times of 40 – 60 days of cow-dung fed digesters in relatively warm areas (e.g. Kenya [24]). In temperate areas microorganisms need more time for duplication and a higher HRT is advised.

The total digester volume that a household requires can be calculated by the HRT that is locally advised and the desired gas storage volume [20]:

$V_F = V*HRT + V_{desired\ storage}$

The HRT depends on the temperature and type of feedstock and the daily volume fed depends on the availability of feedstock or the cooking requirements.

2.2.3 Gas pressure

The pressure in the digester needs to be high enough to overcome the resistance in the piping and create a sufficient flow from the digester to the stove. The pressure is created when the biogas that is produced pushes the slurry level in the digester holder down, causing the compensation volume level to rise [28]. When gas is consumed the pressure decreases. Hence, the pressure is lower after cooking than before. When the gas is withdrawn, the slurry flows partly to the digester and the slurry in the compensation volume flows partially back to the digester. A higher column of digestate in the expansion chamber means that a higher gas pressure can be reached.

A digester has a maximum pressure that can be reached [28], which mainly depends on:

- the maximum level of the compensation volume;
- the minimum slurry level, which is determined by the height of the top of the outlet canal This is indicated by *lower slurry level* (*LSL*) in Figure 4.

When gas is produced at the maximum pressure the gas escapes through the outlet canal. The pressure of brick-dome type digesters can reach values over 100 cm $H2O$ (roughly 10 kPa, see appendix 8.6.1 for pressure unit conversion). Pressures of bag type digesters usually do not reach more than 5 cm $H2O$ (roughly 0.5 kPa). A stronger flame can be reached when the pressure is higher. A low pressure can limit the cooking process.

2.2.4 Gas balance

Not all gas that is produced reaches the stove. A small part of the gas production occurs in the aerobic expansion chamber, because the methanogenic microorganisms are not instantly eliminated. Furthermore, leakage can occur in the piping, the connection with the stove or in the gas holder. [17] When gas production takes place when the gasholder is full the gas escapes through the outlet canal. In these cases gas is emitted to the atmosphere. Changes in the net stored volume within a time frame should also be taken into account. This gives the following biogas balance:

$BY = V_{total\ produced} + V_{unused\ potential}$ where $V_{unused\ potential}$ is a theoretical volume that could have been produced additionally. The produced volume can be considered as:

$V_{total\ produced} = V_{consumed} + V_{leaked} + V_{escaped} + V_{produced\ expansion\ chamber} +/- V_{storage}$

When the gas that is produced in the expansion chamber after leaving the digester is excluded ($V_{produced\ expansion\ chamber}$), a longer period is considered and therefore the stock changes are negligible ($V_{storage} = 0$), the gas is used frequently enough ($V_{escaped} = 0$) and there is no leakage in the digester leakage ($V_{leaked} = 0$) the produced volume can be measured by the gas that is consumed by the stove:

$V_{total\ produced} = V_{consumed}$

Usually the gas volume is measured in Nm3, which means the volume the gas with a certain pressure would occupy when it would be under atmospheric pressure (p_0, on average 101.3 kPa). To determine the normal volume of a volume of gas under a certain pressure the absolute volumes (m^3) should be corrected for this pressures (see appendix 8.6.2.1). The normal volume that a certain volume with pressure p_1 would occupy under atmospheric pressure would be:

$V_{p0} = V * P/P_{p0}$ where V_{p0} is expressed in Nm^3 and V is the same volume under pressure 'p'.

2.2.5 Biodigester types

Many biodigester types have been designed. A division can be made between solid-state digesters and flexible digesters. Solid state digesters are made from a rigid structure that can operate under higher pressure, that is maintained by a costly expansion chamber. The brick-dome type digester, which is widespread in SSA, is locally made of bricks and are assumed to have a longer lifetime. For the Kenyan market the Kenbim model is developed. The design of this brick-dome digester is instructed to most masons by the national biogas program to spread the technology in the country. The GesiShamba model of Simgas, a Dutch biodigester construction entrepreneur (BCE) of prefabricated solid-state digesters, is one of the alternative solid-state digesters that is installed in many regions. It is characterized by the fact that the expansion chamber is built on top of the digester volume.

Recently, many flexible digesters, also described as tubular or bag digesters entered the biogas market. These prefabricated digesters do usually not have an expension chamber, and therefore lack significant compensation volume. Pressure can be created by placing ballast on the gas storage bag. An example of a flexible digester is the bag digester that is produced by the German company Rehau (Figure 5Figure 1, left). A third type of common digester types are floating-drum digesters. These digesters have a gas solid storage volume that is mechanically increasable when more gas is produced, thereby increasing the storage volume. An example is the Bluefalme digester (Figure 5, right), which was developed by the Kenyan company Kentainers and is made of hard plastic. The Blueflame digester type does not have an expansion chamber, since pressure is maintained by the weight of the drum.

Figure 5: picture of the Rehau bag digester t ype (left) and two versions of the Blueflame floating dome type (right). Pictures from personal archieve.

Improved or adapted versions of existing digester types have been introduced, e.g. digesters that perform better under certain conditions, such as a low availability of water (appendix 8.2.3.4).

2.2.6 Investment costs

Prices of digesters depend on the size, type, the location of installation and the contractor. Prices typically range between $550 and $900 for brick-dome types (in 2011) in SSA countries. The investment has a payback period (PBP) typically of 2 – 3 years [29]. Income is mainly created by the following aspects:

- savings on conventional fuels, such as charcoal, which are replaced by biogas;
- savings on fertilizers, which are replaced by bioslurry;
- higher crop yield due to the use of bioslurry.

Although the PBP of the investment is positive the investment remains an obstacle for the adoption of the technology. Many households do not have the required savings and getting access to credit is often problematic, since credit funds are often not available or the interest rates are high.

2.2.7 Domestic biogas sector

Since 2008 Africa Biogas Programme Partnership has been working on setting up a biogas sector in SSA countries. Since, all national programs under the partnership have been working on educating masons to build digesters, support local biogas entrepreneurs and to fulfil a coordinating role in maintaining the quality of the market, together with partner organizations and governments. Also, subsidy schemes have been used to stimulate the market [10]. To maintain the quality, quality control surveys are done. In Kenya, for instance, this is outsourced to *Technobrain*, a local call centre [30].

All BCEs that want to sell biodigesters under the name of the national biogas program need to register and guarantee the quality of the products and receive training. The national programs monitor BCEs and the plants that have been built. As mentioned in section 1.3, ABPP and its partner organizations set up researches e.g. on the performance of different biodigester designs.

2.3 Biodigester performance

Good performances of biodigesters are important for a well-functioning biogas market through the following ways:

- Well-performing biodigesters have a high likeliness of being purchased and thus a higher technical-economics potential.
- Well-performing biodigesters satisfy the demands of the customers and have a low probability of dis-adoption [11] (household that stop using the biodigester a certain period after installation), which can harm the image of the local domestic biogas sector [7].

2.3.1 General performance definition

In many natural sciences performance is defined as useful output per total input. The main aim of the domestic biogas programs is to replace conventional fuels with clean alternatives (useful output) and hence the production of an abundant supply of biogas that is able to replace the conventional type of cooking. The secondary aim is to improve the agricultural activities of the households by applying bioslurry (useful output). A good image of the technology is also important, which comes along with satisfied owners and a minimum of negative aspects. That means that all cooking comfort must be maintained or even improved, during the whole year, and the financial picture must be attractive. This can be considered as minimizing the negative outputs.

The SDGs on which the development of domestic biogas relies also imply that also other aspects are important, such as the effect of the digester on the environment, climate and the development of the local economy. Hence, the general definition of domestic biodigester performance can be described in the following way. Performance includes a biodigester type with:

- an optimal and stable production of high-quality biogas and bioslurry;
- a minimum of properties that limit the comfort, finance and other aspects that are important to the wellbeing of the owner;
- a positive effect towards the environment and the local economy.

In section 3.1.2, a research specific definition will be defined.

2.3.2 Previous studies

Two performance measuring studies (Rwanda, 2015 and Tanzania, 2015, by two different coordinators) have been done, which has led to one public report. The Rwanda study is based on the comparison of the performances between three local types, of which one brick-dome type and two bag digester types [15]. The Tanzania study compares an old brick dome model with a new version [17]. Both reports present a wide overview of the important parameters. Beside these studies some other sources have been found that provide suggestions for important parameters. Also, a publication of Murdoch University on the development of a biodigester type decision making tool under varying conditions [20] and a number of other publications (e.g. dis-adoption rates of biodigesters [11]) describe important parameters.

Many of the parameters suggested in different researches overlap. Remarkably, many overlapping parameters (e.g. *ease of use of digester* versus *expertise required for operation*) are defined differently and use other measures (e.g. *net present value* versus *payback period*), which is probably due to the fact that the studies had different coordinators. For some parameters, it is not clear what the added value is, since another parameter already covers a part of the importance (e.g. *state of digester* versus *robustness*). The next paragraphs contain an overview of all parameters that are described in literature selection of parameters. The approach is to provide an overview of the whole performance profile by a selection of a limited number of parameters. These will be called *performance indicators*. Parameters that are not expected to vary between different digester types are excluded. The described parameters will include technical, operational, financial and environmental or economical parameters.

2.3.3 Technical parameters

In previous studies the absolute gas flow related to the input of dung (TP1 in Table 1) or to the volume of the digester (TP2) have been described as parameters that are important for determining the technical efficiency of the digester. Also, the stability is described, which implies that the digester is expected to have a minimum vulnerability to non-optimal feeding and temperatures and temperature dynamics (TP3). The pH levels of the substrate (TP4) have been used as indicator for a stable AD process. In one study the density of the biogas was measured to estimate the methane content. During both studies form 2015 an approach of gas production efficiency was made by comparing the degradation of (volatile) solids of the substrate and the digestate (TP6). In addition, the pressure that a biodigester provides (TP7) is described as an important parameter for describing performance, since high pressures provide more cooking comfort. It is also desired that the pressure remains high during cooking (TP8).

Code	**Technical Parameters**	Classification	Source
TP1	Gas flow per kg of cow dung / biogas production eff.	Performance indicator	15 17 20
TP2	Gas production per digester volume	Under TP1, FP1	20
TP3	Sensitivity to temperature fluctuations (stability)	Performance indicator	15 17 20
TP4	pH levels	Under TP3	15
TP5	Gas density	Performance indicator	17
TP6	Total solids / volatile solids degradation	Under TP1	15 17
TP7	Gas pressure (maximum & average)	Performance indicator	17
TP8	Constancy of gas pressure	Under TP3, TP7	20
TP9	Energy returned on energy invested	Under FP1, EP6	20
TP10	Gas storage volume	Performance indicator	17 31
TP11	Nutrient content of bio-slurry	Performance indicator	15
TP12	Pathogen reduction	Performance indicator	15

Table 1: overview of technical parameters. The marked cells are parameters that are considered as performance indicators (yellow = included in research scope, grey = excluded, see section 3.1.3).

The absolute gas flow related to the dung input (TP1) can be used to describe the gas production efficiency. Gas production per digester volume is unnecessary when oversizing of a biodigester is already covered by the high installation costs (FP1). The pH level is an example of a measuring tool for the stability (TP3). Also, constancy of gas pressure (TP8) and return on energy investment (TP9) can be classified under other parameters and therefore are not considered as individual performance indicators.

Digesters that have a large gas storage volume (TP10) provide owners more possibilities regarding the timing of the cooking.

Beside the technical quality related to biogas the slurry can have different qualities. When the slurry has a high nutrient concentration (TP11) the fertilizing value is better. When the reduction of pathogens (TP12) during the process is insufficient a toilet connection is inadvisable in case the slurry is used for crop fertilizing.

2.3.4 Operational parameters

A low user comfort can be an obstacle for purchasing. For some digesters feeding takes a lot of time or certain actions are required before cooking or feeding is possible, such as placing of ballast on the gas storage for sufficient gas pressure, to which a number of indicators (OP1, OP2, OP3, OP4 in Table 2) are related. For certain digesters the site easily gets polluted by the dung spilled during feeding (OP5). A number of parameters relate to the physical quality of the product (OP6, OP7, OP8, OP9), construction time (OP10), provided cooking time (OP11) and surface of the digester (OP12).

Code	**Operational Parameters**	Classification	Source
OP1	Ease of use (e.g. feeding, discharge, cooking)	Performance indicator	[15] [17]
OP2	Level of expertise required for operation	Under OP1	[20]
OP3	Daily operation time	Under OP1	[20]
OP4	Net time saving due to digester operation	Under OP1	[20]
OP5	Cleanliness of the site	Under OP1	[15] [17]
OP6	Robustness	Performance indicator	[15] [17]
OP7	Lifespan	Under OP7	[20]
OP8	Annual maintenance required	Under OP7	[20]
OP9	State of the digester (e.g. wear & tear)	Under OP7	[17]
OP10	Construction Time	Under FP1	[20]
OP11	Proportion of cooking / energy requirements met	Under TP1	[15] [20]
OP12	Total surface	Performance indicator	[32]

Table 2: overview of operational parameters. The marked cells are parameters that are considered as performance indicators.

Ease of use is a comprehensive parameter that covers a number of other parameters. Robustness is the most general parameter covering the physical quality and vulnerability to damage. Cooking requirements met depends on the amount of gas production (TP1). The negative aspects of a long construction time is mainly that the construction is complex, which is covered by investment costs (FP1). Total surface is not covered by any other parameters and are considered as performance indicator.

2.3.5 Financial parameters

Some proposed financial parameters describe the different cash flows due to savings (FP2, FP3, FP4, FP5 in Table 3). Many parameters (FP6, FP8, FP9, fP10) describe a way of expressing the financial performance. Most of them are measures that can be calculated by the following parameters :

- *investment* (I) and *annual costs* (C), which are usually zero;
- *operation and maintenance* (O&M);

- *benefits* (B) from savings on fertilizers and fuels and income from increased crop yield;
- others: *discount rate* (r) for investments and *lifetime* (L) of the product.

For instance, the *Net Present Value* (NPV) can be calculated (assuming constant annual benefits and costs) by [33]:

$$NPV = -I + \frac{B-C}{\alpha} \quad \text{where } \alpha = \frac{r}{1-(1+r)^{-L}}$$

NPV is thus a factor that depends on the previously mentioned parameters, of which only investment costs is determining for the performance profile. Savings (B) are dependent on the production of gas and slurry (covered by other parameters) and on the conventional way of cooking and fertilizing, which is condition specific and does not depend on the digester type but on the household and the O&M costs are considered as result of the robustness of the plant (OP7). Discount rates for economies of rural developing areas are not expected to be very significant. Therefore, investment is the only financial that is considered as a performance indicator.

Code	**Financial Parameters**	Type	Source
FP1	Investment / Installation Costs	Performance indicator	15 17 20
FP2	Annual Savings	Under TP1, TP11, FP1	20
FP3	Impact of crop yields on savings	Under FP2,	15
FP4	Fuel wood savings	Under FP2	15
FP5	Financial return in energy and fertilizer value	Under FP1, FP2	17
FP6	O&M costs	Under OP7	15 17 20
FP7	Net Present Value (NPV)	Under FP1, FP2, FP6	20
FP8	Simple PBP	Under FP1, FP2, FP6	20
FP9	Affordability	Under FP1, FP2, FP6	20
FP10	Savings required to meet capital costs	Under FP1, FP2	20

Table 3: overview of financial parameters. The marked cells are parameters that are considered as performance indicators.

2.3.6 Economic and environmental parameters

Effect on the society (EP1 in Table 4) is a performance indicator that some covers (EP2, EP3, EP4). Using local materials (EP5) is only important as benefit to employment generation (EP2) and environmental aspects (EP6). The environmental impact is explained by two indicators. One explains the local environmental benefits (EP6) and the other the effect of the biodigester in the framework of global warming (EP7).

Code	**Economic and environmental parameters**	Type	Source
EP1	Impact on society	Performance indicator	15
EP2	Employment generation	Under EP1	20
EP3	Private sector development	Under EP1	17
EP4	Capacity building of local technicians	Under EP3	17
EP5	Proportion of required materials available locally	Under EP2, EP6	20
EP6	Impact on (local) environment	Performance indicator	15
EP7	Potential for GHG reduction	Performance indicator	17

Table 4: overview of economic and environmental parameters. The marked cells are parameters that are considered as performance indicators.

A total of fourteen indicators form a performance profile that covers all aspects important to the performance of domestic biodigesters, including seven technical parameters, four operational parameters, one financial parameters and three economic and environmental parameters. The codes of these parameters are marked (grey or yellow) in table 1 – 4.

2.4 Measuring tools

Tools are required to obtain data on different performance indicators. In this study these are called measuring tools and can include both technical and manual tools. Some measuring tools record data during a certain time frame and others only take one record. The following paragraphs describes the measuring tools that are described by different sources.

2.4.1 Biodigester database

The national biogas programs under ABPP introduces new plants in a central databases. This is done for monitoring the quality of the plants and organizing after sale service. The information is recorded by the customer service of the national program and provides a set of data on every individual plant. For Kenya the database is recorded by Kenya Biogas Program (KBP).

2.4.2 Survey

One straightforward method of obtaining data on performance indicators is by survey. There are experiences with performing surveys among biodigester owners in Kenya [34–36]. One clear example is the *Domestic Biogas User Survey* from *COVARD consultants* that was organized in 2014 by the former *Kenya National Domestic Biogas Programme (KENDBP)* and the *Kenya National Federation of Agriculture Producers (KENFAP)* as part of the program evaluation. The aim of the Domestic Biogas User Survey was to research the socio-economic benefits of domestic biogas, the fuel situation and history of the households, and other components, both qualitatively and quantitatively [34]. Another example of using a survey for obtaining data from biodigester owners is the *Biodigester User Survey of Zambia* that was performed by *EcoTech Solution* consultants in 2016 for SNV and its Zambian partners. The aim of the study was to obtain information on socio-economic characteristics and many household-related issues, such as pre-construction activities, livestock and sanitation [35].

Both experiences show that the households are approachable, willing to participate and that the obtained data can produce reliable figures. The disadvantage is that the survey is only a single moment record and that the variations in time of certain performance indicators are hard to measure. An important example is monitoring the relative gas production, which requires both data on the daily dung input and data on the daily gas production. For instance, the dung input is not the same every day or might be forgotten.

2.4.3 Logbook

For some indicators monitoring over a longer time can be useful in analysing the performance of a certain digester type on this. One way to do this is to create a multiple-day alternative on the field survey, in order to measure a number of parameters over a longer time, in this study called *logbooks*.

User forms, a similar measuring tool, was previously used in the field [15]. A logbook records a number of parameters that needs to be recorded daily by the responsible persons of the households. Instructions will be given to provide the essential information.

2.4.4 Data logger

A technically advanced way of obtaining data on biodigester performances is using data loggers. Data loggers are devices that obtain data on technical parameters that can explain different performance indicators. Twelve data loggers were developed and produced by the Dutch company Pronon in 2014 for ABPP [37]. The device is designed to endure all outdoor conditions. It was decided to monitor a number of parameters, including [18]:

- consumption of biogas (liter / minute), by a flow meter;
- pressure in the biodigester system (cm H2O), by a pressure sensor;
- ambient air temperature (degrees Celsius), by a temperature sensor;
- internal digester temperature (degrees Celsius), by a temperature sensor attached to a cable.

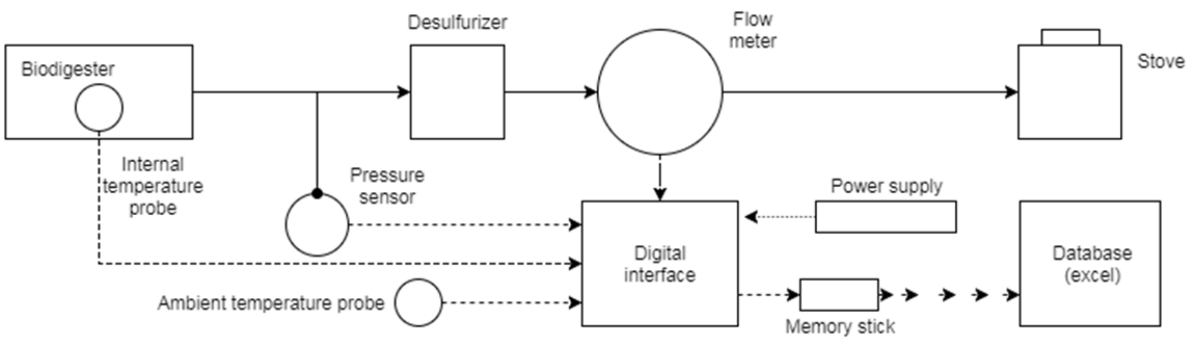

Figure 6: schematic visualisation of ABPP data logger developed by Pronon in 2014. Figure from personal archieve based on: [37,38].

The ABPP data logger is a device (Figure 6: schematic visualisation of ABPP data logger developed by Pronon in 2014. Figure from personal archieve based on: [37,38]Figure 6) with a number of fixed components, which is as a whole placed in series with the biodigester and the stove. This requires cutting of the biogas piping and connecting the input and output of the data logger with the piping of the biodigester system. Directly after the point where the biogas piping is connected to the data logger there is a T-junction that connects with a pressure sensor, which consists of a counter-pressure membrane with a chip that records the pressure delivered by the biogas [37].

After T-junction a desulfurizer and a second hand diaphragm type flow meter [37] are connected in series. The corrosiveness of the H_2S in the biogas is a threat to the metal compartments of the flow meter that are vulnerable to corrosion [37], which is why the desulfurizer is installed before the flow meter. The flow meters were recalibrated because of their age [37]. After the flow meter the biogas flows into the other end of the cut piping, which goes towards the stove. Note that the effect of the pressure on the actual volume measured (appendix 8.6.2.1) needs to be taken into account for accurate records. Ambient air temperature is measured by a sensor is installed at the data logger and a temperature 5 – 10-meter-long cable sensor measures the slurry temperature when inserted in the biodigester.

Date	Time	Sl. T	Am. T	Pressure	Flow	Voltage
dd-mm-yyyy	hh:mm:ss	℃	℃	cm H2O	l/min	dV
16-01-15	21:58:36	21.9	21.2	56.5	0	126
16-01-15	21:59:36	21.8	21.2	56.5	0	126
16-01-15	22:00:36	21.7	21.2	56.6	0	126

Table 5: example of parameters recorded by data logger, inserted in Microsoft Excel.

The records of all four sensors are led to a digital data collection device that is connected to a flash disk. The digital device writes the data as a .csv file for every minute (example shown by Table 5). In addition to the mentioned parameters *time*, *date* and *battery voltage* are recorded.

2.4.5 Lab analysis

Lab analysis is described as measuring tool for determining the composition of the substrate and digestate [15,17]. The slurry can be tested on a number of indicators:

- The content of nitrogen, phosphorus and potassium, and other nutrients, are important to the fertilizing value of the slurry.
- The concentration difference of *volatile organic compounds* (VOCs) in the slurry can explain to what extent the AD process has reduced the organic particles and serves as an estimation of the amount of biogas that is produced.
- The presence of a number of pathogens and microorganisms determines the hygiene of applying the slurry.

In the performance measuring study in Rwanda (2015) it became clear that it is important to take samples over a period that exceeds the retention time to get a reliable overview of the substrate (that is fed into the digester) and digestate (bioslurry) composition [15]. This is especially important for reliable figures on the breakdown of VOCs.

2.4.6 Visual observation

The study done by COVARD mentions that research assistants were instructed to take as much records as possible during the visit, in addition to the main measuring tool. This includes information on the state of the biodigester, cooking behaviour, feeding and other information [34]. This type of unstructured method of taking records by visual observation is a method that can provide important information that can be ignored by other measuring tools. This is called visual observation in this study and is added to the list of available measuring tools.

A selection of measuring tools included in this research are given in section 3.1.4.

3 Method

As described in the introduction, the aim of this thesis is to develop a comparative performance measuring method for domestic biodigesters in the ABPP countries. This research includes the following steps in order to come to conclusions:

The first part of the method (section 3.1) describes what the boundaries of this research are by defining a number of scopes. The definition of performance will be redefined to a research-specific definition. The performance indicators that cover this definition will be described. Section 3.2 deals with the general research setup, which includes a description of the selected regions and the aim of every fieldwork session. Section 3.3 describes the interaction between the performance indicators and the measuring tools, and explains which tools can be used per indicator. Also, the measures that are tested per indicator are discussed.

3.1 Research scope & assumptions

3.1.1 Research boundaries

There are a number of limitations to the scope of the research. Firstly, the time frame of three months of fieldwork was a limiting factor to the research setup. Secondly, geographic boundaries were set. The research was conducted for ABPP. Hence, this study focusses on the five countries of the program. Because of travel budget constraints, fieldwork is only done in the East-African region, mainly in Kenya. In section **Error! Reference source not found.**, the applicability of the method for the other ABPP countries will be discussed. proposed measuring method will be designed to suit implementation in all ABPP countries. The results can be useful for other countries with significant domestic biogas sectors (e.g. Nepal, Bangladesh) but this is not the focus of the study.

Domestic biogas incorporates many disciplines (physics, user aspects, finance, biochemistry). In-depth focussing on every discipline can affect the quality of the findings. Therefore, the focus will mainly lie on the technical, operational and financial part. To avoid complex discussions on the biochemistry of the AD process, the composition of the biogas and bioslurry will not be taken into account. Hence, it is assumed that the biogas composition is not significantly different for every digester, which means that also the heating value and specific mass are assumed to be equal for every biodigester. For the slurry, it means that the nutrient compound is equal and the fertilizing values to the soil per mass of untreated dry slurry as well. Also no measuring tools are used that are based on chemical analysis of bioslurry or biogas.

Not all components of the biogas system are assumed to influence the performance of a biodigester. Therefore, only the most essential parts of the digester system (Figure 7) are considered in this research. Different BCEs might sell other stove types and every stove can be installed at almost every biodigester. Differences in stove types are therefore not included in the research. This is also the case for slurry pits. The quality of the piping can affect the performance of the biodigester as well, for instance because of leakage. In this study the piping until the main valve is considered as biodigester. Everything beyond is considered as additional components. The expansion chamber is included in the research, since it is determining for the gas pressure and an important part of the installation costs.

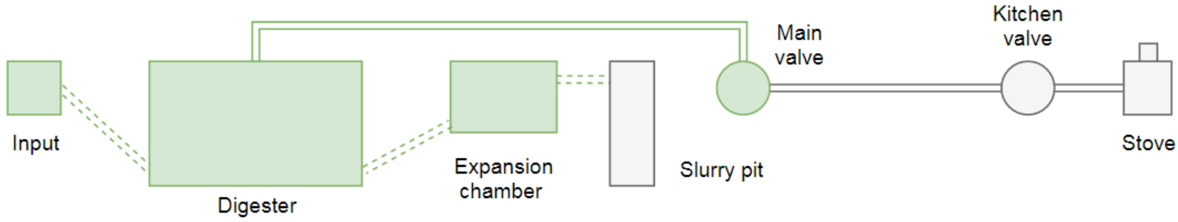

Figure 7: representation of the parts of the biodigester system that are included (green) and excluded (grey) from the research boundaries.

The domestic biogas system can be analysed in the different contexts. Only technical and operational parameters were taken into account, which can be considered as the micro-scale: connection between the product and the household. That means that macro parameters were ignored. Hence, aspects such as greenhouse gas emissions from the system to the atmosphere (which is not expected to vary a lot between different digester types) and local employment effects are not taken into account.

As described the gas production potential of a kilogram of feeding depends on the composition. Since all digesters of the study were fed with similar cow dung it was assumed that the feeding and the BY is equal for all digesters.

$$BY_{dung\ type\ 1} = BY_{dung\ type\ 2}$$

The density of a certain dung type can vary between cows and can depend on feedstocks for the cow. It has been described that the density of cow dung is usually very near to the density of water. Hence, the following assumption was made.

$\rho_{water} = \rho_{dung}$ and $\rho_{dung\ digester\ 1} = \rho_{dung\ digester\ 2}$

3.1.2 Research specific definition of biodigester performance

Considering the four described scopes leads to an adapted definition of biodigester performance for this study, which includes technical, operational and financial aspects.

Biodigester performance is the extent to which the biodigester is expected to deliver the maximum volume of biogas (output) per unit of feedstock (input) with the least number of disadvantages (negative output) that affect the households comfort of living and finance.

Considering the individual performance indicators mentioned in section 2.3, three technical parameters (gas density, nutrient content of slurry and pathogen reduction) and all of the selected economic and environmental parameters will be ignored.

3.1.3 Selection of performance indicators

Comfort of living can be considered a broad concept, including aspects that aspects that describe the direct use of the biodigester (e.g. feeding), but also indirect aspects (e.g. whether the household needs to adjust its way of cooking). Taking into account the adapted performance definition leads to a better-defined set of performance indicators that are required for the performance profile, which are marked yellow in table 1 – 4.

First of all, the utility of the biogas is considered as the biogas production relative to the input of raw unmixed cow dung, with average feeding. The first indicator for this research will therefor describe the useful output for the household.

PI 1: Specific gas production (SGP)

Three other technical parameters are important within the system boundaries. First of all, the cooking comfort of the household can decrease when the gas pressure is too low, as well when the storage volume is not sufficient and when the gas production is instable and can be affected by certain temperatures and changes in feeding. Also, the stability of gas production is important. Hence:

PI 2: Gas pressure delivered by the biogas system (GP)

PI 3: Gas production stability (GPS) over time

PI 4: Actual / Effective gas storage volume (GSV)

The stove type affects the extent to which the gas pressure can be useful, but is excluded from the scope of the study. The stability of gas production is considered for changes that can occur from the timeframe of within a number of days until the dynamics between seasons. The effective gas storage volume only focusses on the volume that is stored usefully and is available for cooking. When the gas pressure is too low to withdraw a certain fraction, this fraction is not considered effective storage volume.

The research scopes include the assessment of the affordability of the biodigester, which is determined by the costs of the digester and the financial picture of the household. However, the financial picture does not depend on the digester. The affordability is therefore expressed only as the purchase price of the biodigester.

PI 5: Investment costs (IC)

Three other indicators relate to three less technical aspects of a biodigester and are considered as the operational part of the performance profile. These indicators are important to reduce the extent to which the biodigester interferes in the comfort of living beside cooking purposes.

PI 6: Ease of use (EoU)

PI 7: Robustness (Rb)

PI 8: Surface requirements (SR)

The ease of use does not include any issues directly related to cooking and focusses on the manually actions that are required for operating the biodigester that are usually not part of maintenance by the BCE, such as feeding, slurry irrigation and scum removing. Robustness is the extent to which the biodigester can last long and the maintenance that is required for that. The surface requirements for a biogas system are the last performance indicator.

Using the eight performance indicators in performance measuring makes it possible to have a specific, but clear, overview of strengths and weaknesses of different digester types in these fields.

3.1.4 Selection of measuring tools

A selection of measuring tools that is included in the fieldwork can be made taking into account the scope of the research. Using the KBP database, surveys and logbooks do not require any expertise that is not included in the research boundaries. This also counts for the data logger.

Although slurry analysis is expected to create an accurate insight in both the quality of the slurry and the produced biogas, it is not included in the field work. It requires specific chemical knowledge (excluded by expertise scope) and the method hardly fits in the fieldwork time, leaving no buffer for any backup plan in case of problems during the process.

3.1.5 Defined concepts

ABPP aims to set up field studies in different countries, led by different coordinators. This risks that the studies are based on different assumptions, measures, methods and the use of different equipment. Comparativeness of measuring results indicates the fact that the results of different parallel studies are based on the same standards and the results can be compared to each other.

Companies that sell biodigester systems are called Biogas Construction Entrepreneurs (BCEs). For pre-fabricated digesters, the installer is generally part of the manufacturing company. Brick-dome types are used from local material and the BCE is often the contractor that also constructs the digester or coordinates the construction work. These enterprises are usually much smaller and are often indicated as the constructing masons. Important for this study is that the BCE is the enterprise sells the digesters.

A biodigester does not only consist of a gasholder, an input and output or expansion chamber, but also includes the valve, piping, stove and slurry pits. The biodigester system is defined as the total of all these components.

A performance indicator is one of the parameters that form the performance profile. A measuring tool is a method of obtaining data for one or more performance indicators.

3.2 Research approach

A performance profile was set and a number of appropriate measuring tools were selected. To determine the potential that these measuring tools provide for comparative performance measuring the tools were tested in a number of pilot studies in the field. Four regions were selected to perform four different pilot sessions to achieve a better understanding of the process of using the measuring tools and the quality of the data. In these sessions, the performance of the biodigester was measured according to the eight performance indicators that were selected in section 3.1.4.

Note that the resulting performance measurements are not representative for the performance profiles of the specific digesters that were measured. The main focus is an assessment of the measuring tools. Hence, this research cannot be used to draw conclusions regarding the performance of these digester types.

3.2.1 Field work sessions

Due to the limited budget and time schedule centralization of the fieldwork was desired. The KBP office in Nairobi was selected as the central base for all the research, for a number of reasons. First, the biogas market in Kenya is considered to operate well, providing many options for successful testing of the measuring tools. Secondly, working from Nairobi provides a relatively strong network of KBP / ABPP staff, biogas entrepreneurs and other parties that are useful in the context of this study. Third, Kenya is a country with different climate zones and plenty relatively fertile areas with sufficient water resources. This provides good possibilities for finding good-working biodigesters. Finally, the fact that English is widely spoken is an important advantage for the research.

#	Owner (household or company)	Model	Digester type	Volume (m^3)	County
1	Beatrice Igoki (h)	Kenbim	Brick-dome	10	Meru
2	John Mutwiri (h)	Kenbim	Brick-dome	8	Meru
3	Jushua Iguchia (h)	Kenbim	Brick-dome	6	Meru
4	John Mbaya (h)	Kenbim	Brick-dome	8	Meru
5	Robert Muchemi (h)	Kenbim	Brick-dome	8	Meru
6	Francis Kiambi (h)	Kenbim	Brick-dome	8	Meru
7	Unknown (h)	BSU	Brick-dome	8	Kampala (Uganda)
8	Michael Mari (h/c)	Simgas	Simgas	8	Nyeri
9	Johnson Kibui (h)	Simgas	Simgas	4	Nyeri
10	Rehau (c)	Rehau	Bag type, soil covered	3.2	Kiambu
11	Rehau (c)	Rehau	Bag type, uncovered	3.2	Kiambu
12	Kentainers (c)	Blueflame	Floating drum	3.2	Nairobi

Table 6: overview and description of biodigesters from fieldwork sessions.

In total twelve biodigesters (Table 6) were measured in four fieldwork sessions, of which three studies in Kenyan regions (11 biodigesters) and one study in Uganda (1 biodigester), with a limited travel distance (200 km within Kenya, as shown by Figure 8). The majority of the studies focussed on domestic biodigester owned and used for household purposes. One study focussed on showroom plants of BCEs. For the Kenya studies, all of the five measuring tools were used where possible.

Figure 8: distribution of field study location over Kenya (right) and Uganda (left). Source of map: Google Maps.

The first step in the organisation was the selection of a region that is appropriate for the aim of the study. A pre-selection of biodigesters through the national biodigester database was made, which is the KBP database for Kenya. In the pre-selection, the following aspects were taken into account:

- The distance of the household's location to the desired regional base of the study;
- The indications on how the biodigester is functioning according to the database;
- Other aspects, such as number of cows and the composition and age of the family and its members.

A first selection took place based on a limited distance of the household to the region base and the absence of any signs of malfunctioning. This selection was narrowed down with the help of the local call center *Technobrain*. During this selection, the household were asked questions concerning:

- Whether the plant is functioning well (second check) and any problems were reported recently;
- Their willingness to participate in the research;
- The exact location of the house.

Local BCEs have assisted the research in the Meru and Karatina field studies. The selection of the biodigester was adapted to the professional network of the BCEs. From the list of households suitable for research, the BCEs with the most corresponding plants were contacted to assist in the study. The BCEs have delivered assistance in finding the plants and installing and uninstalling the data logger, for which they received a daily reward.

The last selection criteria before installing was determining whether the plant is expected to be free of leakage. Leakage would mean that the following given equation cannot be assumed and the gas consumption is not representative to the gas production. To exclude the possibility of leakage a pressure test (appendix 8.3.1) was done for plants with indications of leakage and the owners are asked whether they use the gas daily. Hence, there is a high probably that $V_{leaked} = 0$ and $V_{escaped} = 0$. In that case $V_{consumed} = V_{produced,net}$.

Once the possibility of leakage was excluded the installation of the data logger and the explanation of the logbook took place. The installation required the connection of the data logger to the piping of the biodigester in series between the digester and the stove (Figure 9) and connection to the battery and solar panel as power supply.

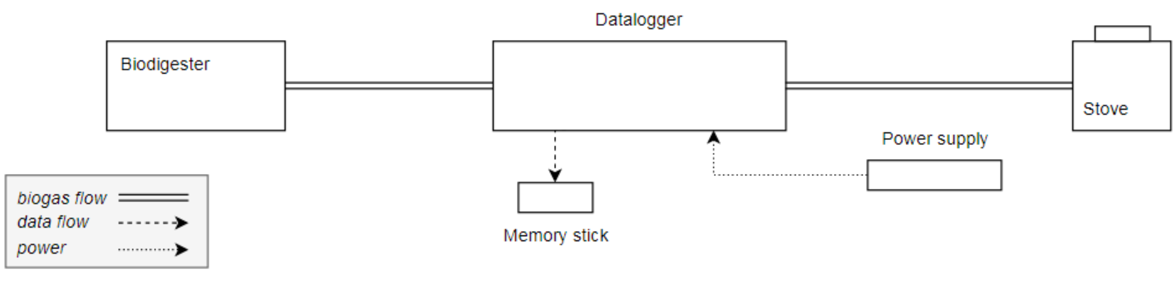

Figure 9: schematic visualisation of the position of the data logger relative to the other system components.

During the measuring phase the functioning of the data logger was checked approximately once a week and visual observations were made during the whole phase when necessary. After the measuring phase the data was retrieved, the data logger was uninstalled, and the ends of piping were connected again. The last step consisted the collection of logbooks and performing the final survey.

3.2.1.1 *Meru county*

The first field work session was performed in Meru in central Kenya (Figure 10), with the aim:

- To find out how all measuring tools work and detect frequently reported problems;
- To find out which parameters (e.g. outside temperatures, dung input) can be standardized in order to get comparative data;
- To observe how much difference in parameters there is between a selection of households with the same type of biodigester;
- To determine what kind of research organization (distance between households, timing of visits, cooperation with BCEs) is recommended.

The Meru region was selected because the KBP staff described Meru county as a region with many well-functioning biogas plants. There is a good local economy and the water resources are sufficient, increasing the success rate of biogas development. Also, from the six plants four had the same volume, creating possibilities for observing the effect of other variables on the process. The dung input was not standardized, creating the possibility to monitor the effect of feeding on the performance.

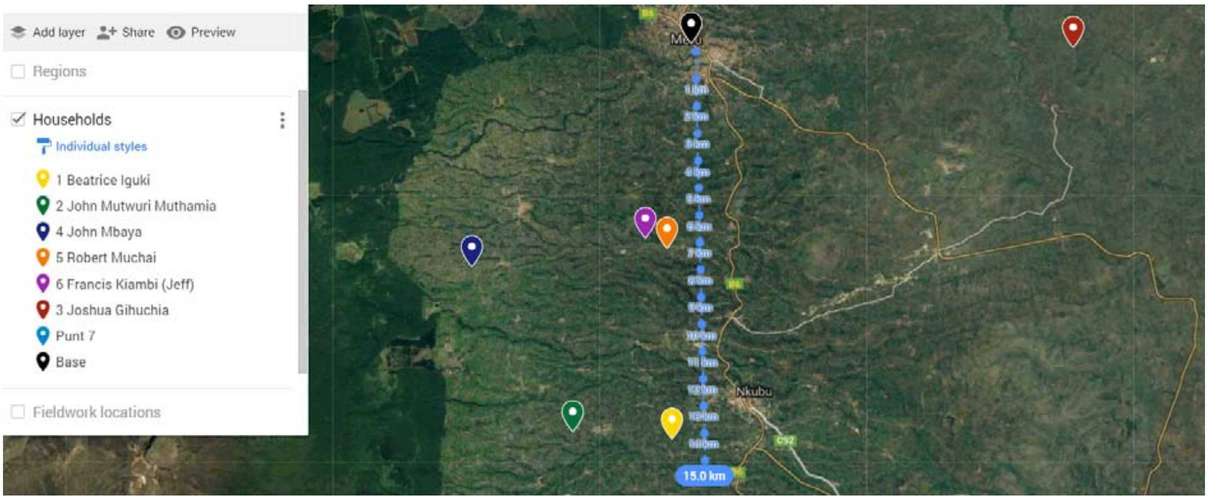

Figure 10: distribution of field study locations in the Meru region and an indication of the radial distance from the base town and the biodigester owners. Source of own archieve, designed using Google Maps.

3.2.1.2 *Kampala (Uganda)*

A second fieldwork session was performed in the Ugandan capital Kampala, with the aim:

- To use the experiences from the fieldwork in Meru to start up the same type of studies from the headquarters of the national biogas program of Uganda (Biogas Solutions ltd);

- To look for any important differences in both the technical, organizational and cultural aspects between different ABPP countries that can influence the setup of a comparative measuring study;
- To observe what kind of problems appear when a method is exported to another place.

For the study in Uganda the collection of the data was controlled by the Ugandan partner of ABPP. The logbook data did not arrive in time to include it in this research and the surveys were not performed. Therefore, only qualitative data and visual observations are obtained during this study. Due to some drawbacks only one biodigester was measured.

3.2.1.3 *Nyeri County*

In Nyeri county a fieldwork session was done in cooperation with the local technical staff of Simgas in the town of Karatina. Two biodigesters were measured, which were both used by households. One of the digesters (biodigester 8) is part of a Simgas test site, but is used for domestic purposes of the household. The main aim of the session was:

- To find out whether there are any difficulties with adapting the ABPP data logger on other biodigester types than the Brickdome type;
- To learn more about the practices of performance measuring done by Simgas;
- To find out whether the data produced by the Simgas flow meter shows equal results to the ABPP flow meter.

Karatina (Nyeri county) has a comparable climate to Meru country and similar socio-economic conditions.

3.2.1.4 *Nairobi & Kiambu county*

In the last period of fieldwork a total of three showroom digesters were monitored in Nairobi and the surrounding areas, of which two bag type digesters from Rehau and one floating drum type with the name Blueflame, produced by Kentainers. The aim of these sessions include:

- To find out whether there are any difficulties with adapting the ABPP data logger on low-pressure biodigester models and to try out the survey questions for a variety of digester types;
- To see whether a biodigester that functions as showroom digester is suitable to be part of a performance measuring and whether there are any additional advantages of not having a household involved in the measuring study;
- To discuss with BCEs what their interests in performance measuring would be.

During this session not all data loggers were in use. Therefore an additional experiment was done at the Blueflame. As visualized in 10 data loggers were installed in series to find out whether the results of two data loggers match.

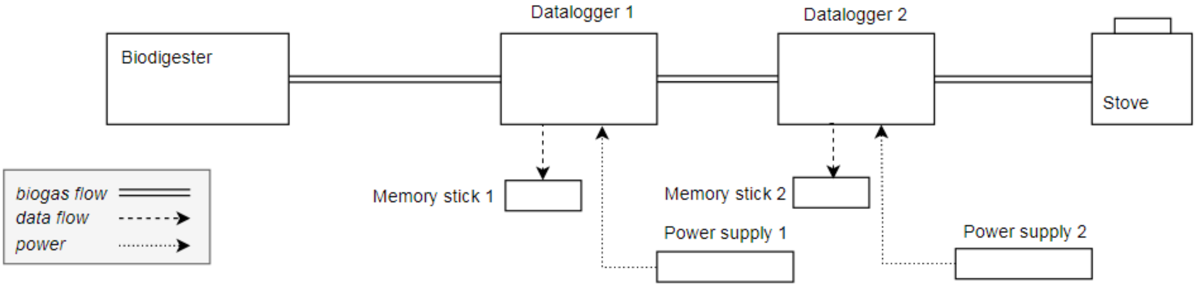

Figure 11: schematic visualisation of double in series installation of data loggers for biodigester 12.

Two data loggers were installed at two identical Rehau digester designs (figure 11). An additional experiment (appendix 8.3.2) was performed during the field study at the Rehau test site.

3.2.2 Desired output

For the testing of the measuring tools, two analyses were made. One focusses on analysing the process of using a certain measuring tool, since this aspect determines whether a measuring tool has the potential to be used in a measuring method. The other analysis focusses on the quality of the data. When the quality of the data generated by a measuring tool is disappointing, it means that it does not have much potential to operate in a performance measuring method.

For both the process and the data quality analysis the scores will be rated by the following ordinal scale:

- 5 (very high / excellent);
- 4 (high / good);
- 3 (moderate ;
- 2 (low / bad);
- 1 (very low / very bad).

3.2.2.1 *Process analysis*

The proposed performance measuring method should be attractive to use for ABPP. Per measuring tool an assessment of the process, which assesses the following stages:

- The pre-measuring phase, which includes all actions that are required to start with the data collection. This can be the installation of a tool, but also the preparation that corresponding households need to take in advance.
- The data collection or measuring phase. This includes keeping the measuring tool in operation and retrieving the data. Also, the efforts that households need to make are taken into account.
- The data analysis phase, which includes all efforts for processing, organizing of the data and other preparations for drawing conclusions.

A process score is determined depending on four criteria. In order to compare the end scores to one single score for the process of every tool a weighting factor is attached to each criterion. One of the criteria is the *simplicity*, since it was stated by ABPP that the method should be usable for average biogas technicians in ABPP countries, without significant research expertise. A complicated process is likely to have drawbacks and errors somewhere in the process that can obstruct data collection without errors. This can be fatal for the data collection or the academic reliability of measuring studies. Hence, simplicity is more important than the other factors with an estimated weight of 40% of the total score.

Another point of concern is that the data collection requires the cooperation of households. Since the image of biogas technology is crucial for the success in the region it is important that a the measuring tools of a method do not lead to negative attitudes. The privacy and freedom of the household should be respected to a certain extent, so the rate of *intervention* should be limited. Although the image of biogas is important to consider, experiences from the field showed that most households are often welcoming and interested in the purpose of the study and are willing to assist in any way they can. The weighting factor that is attached to this criterion is only 10%.

Performance measuring requires time and financial investments. The biogas programs operate using resources for development purposes. As the third and fourth criterion, a*ffordability* and *time requirements* of every measuring tool will be rated. Budgets can be tight and also the workforce will be limited for the majority of the national programs under ABPP. Both for affordability and time the weighting is therefore set at 20%. These aspects are not merged because of the possibility that certain programs will have higher budgets while others have more workforce

3.2.2.2 *Data quality analysis*

The data quality was rated per performance indicator, and is specific for every measuring tool that can be used for that indicator. The quality of the data is rated on two aspects.

Firstly, accuracy is defined as the ability to detect reliable variation in performance scores between different biodigesters. Precision only leads to more accuracy if the recording is representative. For example: measuring the digester pressure with a precision of 0.1 cm H_2O is not adding quality to the data if the standard deviation of the sensor is higher than 0.1 cm H_2O.

Secondly, c*ompleteness* is defined as the extent to which the data collection covers all important dynamics over a certain time. The completeness can be low due to two facts: the number of records is too low to show the desired dynamics of the parameter or a certain measuring tools only records during a limited timeframe while a longer period would be more representative. For every performance indicator, both accuracy and completeness will be determined for all corresponding measuring tools. Both parameters will therefore have a weighting factor of 50% of the data quality single score of every measuring tool on every performance indicator it can measure.

3.2.3 Testing of measuring tools

During the four fieldwork sessions a number of the measuring tools mentioned in 3.1.4 were used to explain the performance indicators selected in section 3.1.3.

3.2.3.1 *KBP database*

The KBP database contains a lot of information, that could help explain different indicators. However, the database is developed for administration purposes and is not focussed on doing any kind of performance measuring. No useful data is provided that can help to explain one of the performance indicators. The only indicator that seems to be measurable is:

- PI 5: Investment costs.

The database will be consulted during the analysing phase of the other measuring tools, although it can be consulted in any time during the measuring study.

3.2.3.2 *Survey*

Theoretically information on all performance indicators can be obtained. However, for some parameters the survey questions are not expected to have any added value. This is the case for gas production stability and storage volume. Since it is assumed that the dung input varies strongly per day and the logbook will be used to measure the dung input dynamics the survey will not be used for this indicator. The performance indicators that can be measured with the survey are:

- PI 1b: Gas production;
- PI 2: Gas pressure;
- PI 5: Investment costs;
- PI 6: Ease of use;
- PI 7: Robustness;
- PI 8: Required surface.

Strategies from the COVARD study (mentioned in section 2.3.2) were considered. It is recommended to only interview the household members responsible for the biodigester. This was taken into account in the Meru and Karatina field studies, although different persons were responsible for respectively cooking and feeding. Also, the survey was kept simple and the questions (table 6) did not have any complex formulations.

Indicative to the gas production, the hours of cooking time were questioned. To monitor the digester pressure it was asked what the pressure usually is before cooking (suitable for households with a pressure gauge) and whether they are satisfied with the gas pressure (all households). The investment purchases and additional costs, to get a detailed overview of the cost profile. The ease of use is a more complicated and arbitrary indicator. To get to know more about the negative aspects of the biodigester it was asked whether the consequences of owning and using a biodigester bothers the household. To monitor the robustness the household was asked on the wear and tear of the digester and its maintenance history. For the surface requirements the households are asked to make an estimation of the space that the system occupies.

1b: gas production	*How many hours of cooking does your biodigester provide you?*
2: digester pressure	*What is usually the pressure before cooking?*
2: digester pressure	*Are you satisfied with the average gas pressure?*
5: investment costs	*Please specify the purchase costs of your biodigester*
5: investment costs	*In case you made additional expenditures, please specify*
6: ease of use	*In what extent does the biodigester have negative influences?*

7: robustness	*Have you noticed any wear and tear?*
7: robustness	*In case you have, please specify*
7: robustness	*In case maintenance has been done, please specify*
8: surface	*How much space does your digester system occupy?*

Table 7: survey questions that were used for obtaining data per performance indicator.

3.2.3.3 ***Logbook***

For different performance indicators data harvesting by logbook provide advantages. The most likely performance indicators that benefit a longer period of measuring by logbook are:

- PI 1a: Dung input
- PI 1b: Gas production

The households were given a logbook containing questions regarding the previously mentioned indicators. For monitoring the dung input and the composition of the digester feedstock, the information in Table 8 was instructed to fill in by the households.

Moments of feeding - Wakati wa kulisha				
Moment of flushing Wakati wa kusafisha	Amount Kiasi	Type Aina	Added water Maji aliongeza	Person Mtu
9:45 am	*1 bucket (21 kg)*	*Cow Dung*	*10 litre*	*Joseph*
3:30 pm	*3 buckets (63 kg)*	*¾ Cow Dung ¼ Pig Dung*	*30 litre*	*Catharine*

Table 8: example of logbook notes for feeding from logbook instruction manual.

The dung must be weighed to know what the total mass of the feedstock is. The households have received weighting scales and were instructed to sum up the total mass of the dung for every day. The cooking periods and intensity were monitored by filling the information from the instruction of Table 9.

Moments of using biogas - Wakati wa matumizi ya biogas				
Starting time Kuanzia	Duration Muda	Intensity Kiwango	Purpose Kusudi	Person Mtu
8:15 am	*1:15*	*0.5*	*Cooking*	*Peter*
1:30 pm	*0:30*	*2*	*Cooking*	*Catharine*
4:00 pm	2:00	0.75	Biogas Lamp	Peter

Table 9: example of logbook notes for cooking from logbook instruction manual.

The participants were instructed to record the start and duration of all cooking moments, including small meals and boiling water. The intensity is explained as the rate of opening of the stove and thus the size of the flame. Also, the purpose was requested as metadata for the data logger flows. In order to be able to retrieve unclear notes the name of the person was requested as well.

It was decided to limit the logbook time, since it was expected to require a relatively high participation of the household, which is not desired. The logbook period was halve that of the data logger time, since this was assumed to provide sufficient insights to have reliable data for calculating the relative gas production.

3.2.3.4 *Data logger*

All technical parameters are expected to be explained by data logger, except for the dung input. The data logger does not contribute anything to one of the operational parameters.

- PI 1b: Gas production;
- PI 2: Gas pressure;
- PI 3: Gas production stability;
- PI 4: Gas storage volume.

Data loggers were installed at the start of the process. Check-ups took place approximately once a week. The data was retrieved at the end during the uninstallation.

3.2.3.5 *Visual observation*

In theory visual observation can explain many parameters. However, the longer-term parameters are assumed to be impossible to explain, since visual observation is very time consuming and only focussed on short moments. Therefore the following parameters are explained by visual observation:

- PI 1a: Dung input;
- PI 1b: Gas production;
- PI 2: Gas pressure;
- PI 6: Ease of use;
- PI 7: Robustness;
- PI 8: Required surface.

Since travelling to the households appeared to be a major part of the efforts of data collection, it pays off to take the most possible records of the households during visits. This was also advised in the survey performed by COVARD, as well as recording information that was not necessarily planned to record. That opportunistic approach is also used during the fieldwork of this study, where visual observation is a tool that is rather an improvised tool that is used for collecting data where possible.

3.2.4 Performance measures

A first selection of measures was tested to find out how the performance measuring could be quantified and how digester types can be compared. In the results section the advantages and disadvantages will be described per measure of every performance indicator.

3.2.4.1 *Measures for technical indicators*

An overview of the measures tested for the technical measures is given in Table 10. For measuring the first performance indicator (specific gas production) the most obvious unit is volume of gas per mass of input. This is the extent to which the theoretical BY of the input can be reached. Since water does not have a BY and different rates of mixing might be used it is expressed as liter of gas per kg of unmixed cow dung. The flow meter of the data logger provides data on the absolute gas consumption in a certain time. The recorded flows can be summed up. For the survey the volume can be measured by recording the daily cooking time and calibrating the volume that is represented by an hour of cooking with the data logger data. An expression that can be made from the logbook data is intensity multiplied by the cooking time from the logbook (intensity-hours), which can represent as an absolute gas flow after calibration by data logger flow records.

Technical measures	1 SGP		2 GP	3 GPS	4 GSV
	1a DI	1b GC			
Database					
Survey		Cooking h/day	1-5 scale		
Logbook	Kg raw dung /day	Int.*hours/day			
Data logger		Liters/day	P,average	Feeding balance; Temp sensitivity	M^3
Visual Observation	Kg raw dung /day	Int.*hours/day	1-5 scale		

Table 10: proposed measures for measuring the technical indicators by different measuring tools.

The gas pressure is monitored by a 1-5 scale for the survey and visual observation. The pressure records from the data logger can be translated to the pressure performance by calculating the average pressure. Gas production stability requires a more complicated unit. The decrease in feeding caused by instable feeding can be calculated expressing the (im)balance of feeding, including both overfeeding and underfeeding:

$$\textit{Feeding balance} = | M_{\textit{unmixed dung}} / M_{\textit{dung advised}} - 1 |$$

Instability would be characterized by a certain decrease of specific gas production due to instable feeding. The instability due to temperatures can be monitored by relating the temperature swings in the digesters to the swings in ambient air temperatures:

$$\textit{Temperature instability} = \Delta T_{digester} / \Delta T_{ambient}$$

The practical storage volume can be expressed in liters, in the same unit as it is provided by the manufacturer.

3.2.4.2 *Measures for operational & financial indicators*

For every performance indicator one or more measures are proposed that can express the performance in a concrete number. An overview is presented in Table 11. The usability of the measures will be discussed with the assessment of the data quality in section 4.2.

The investment costs are measured in the expenditures for in installation in dollars. The ease of use is monitored using a 1 – 5 scale that represents relatively low and high ease of use. The robustness is expressed by estimating the lifetime of the digester, taking into account a number of things

- The current age of the digester from construction;
- The state of the digester, including wear and tear or other damages;
- The maintenance that has been done to bring back the digester in an acceptable state.

The rate of damage and maintenance over the current age can be extrapolated to make an estimation of the lifetime. For the surface requirements of the digester it is obvious to express it the performance m^2. However, some digesters are larger and produce more useful output (biogas). Relating the surface to the digester volume is therefore more reliable.

Operational / financial measures	5 IC	6 EoU	7 Rb	8 RS
Database	$			
Survey	$	1-5 scale	Exp. lifetime	m^2/m^3
Logbook				
Data logger				
Visual Observation		1-5 scale	Exp. lifetime	m^2/m^3

Table 11: proposed measures for measuring operational & financial indicators.

3.2.5 Options for improving measuring tools

Although the field work sessions provided insights in the process and data quality of using existing measuring tools, (technological) developments can lead to improvement of existing measuring tools or the development of new tools. A number of interviews was conducted to find out how a number of tools can be developed:

- An interview was conducted with an KBP staff member to find out wat the possibilities are to use the biodigester database for performance measuring. Also the potential role that the call centre *technobrain* was discussed.
- An interview was conducted with the person from Pronon that developed the current data logger for ABPP, to discuss the options and cost profiles for a second generation data logger.
- Two interviews were conducted with two Simgas staff members, since Simgas has worked on its own data logger. The aim was to discuss whether this device produces data that is comparative to the data generated by the ABPP data logger. Also cost indications and the possibilities of developing a data logger according to the preferences of ABPP were discussed.

In addition, the field study in Karatina (biodigester 7 and 8) was used to install the ABPP data logger in series with the data logger that is developed by simgas, to monitor whether the dataloggers produce data that can be used comparatively in one study. Since the Simgas flow meter were not calibrated, the results were calibrated by multiplying with a calibration factor:

$$F_{calibration} = V_{total\ ABBP} / V_{total,Simgas}$$

For every seperated cooking moments the consumed volumes ($V_{t\ ABPP}$ and $V_{t\ Simgas}$) were monitored for both flow meters to find out whether the following equation is representative.

$V_{t\ ABPP} = V_{t\ Simgas} * F_{calibration}$

3.2.6 Survey among biogas experts

Parallel to the measurements in the field and the described interviews, a survey was conducted among biogas experts, using the ABPP network. A number of questions were asked:

- The respondents were asked to rate the eight selected performance indicators from most to least important, to find out whether each indicator is expected to be determining for the performance profile.
- There was the option to suggest other performance indicators that were not included in the proposed selection.
- An additional question focussed on the importance of the quality of the biodigester relative to the quality of the BCE as a whole, to find out wheter parameters outside the scope are

The observations will be used to discuss whether the proposed selection of measuring tools will eventually be a good representation of the biodigester performance.

4 Results

Fieldwork was done to collect data for explaining the performances in the field of eight performance indicators by five different measuring tools. Section 4.1 will focus on the process of using the measuring tools. Section 4.2 deals with the way of applying these measuring tools for different performance indicators and the quality of the obtained data. Section 4.3 explains which alternatives were found that can add value to the process or data quality of the five measuring tools.

4.1 Process assessment

In this section, the process analysis of the five selected measuring tools will be discussed. First of all, the observations with every measuring tool will be described per tool, taking into account the pre-measuring phase (preparations to make the measuring tool ready to use), the installation or de-installation (in case of), the phase of data retrieving and the analysing phase.

4.1.1 Evaluation of KBP database

The main pre-measuring effort for the database includes the data collection process and making sure that the database is updated frequently. Data is partially collected by phone calls from the KBP customer support centre during the quality control checks of new biodigester. Another part of the data is supplied by the BCEs that build plants under the KBP name, which includes the cost profiles. No additional efforts are required. Using the database is an easy process. The database of biodigesters under KBP is available as excel file that is digitally available for KBP and ABPP staff. The data is registered per year of construction. A certain household can be found with applying selections e.g. on the corresponding region, digester size or village, which makes it easier to find a certain household in a large data sheet.

One problem of analysing the data is the fact that names of the plant owners are not always registered consistently. Sometimes the middle names are registered as surnames or vice versa. In other cases, there was a difference in spelling between the indication given by the person and the database. Because of the size of the database it could require some time to find the information of the right person. In addition, there was the risk of recording information that corresponds to another household.

4.1.1.1 *Key findings*

An overview of the process scores is provided by (Table 12). The database is a tool that is simple to prepare, and very simple to use and analyse. Although it might take some time to find the right household it still requires a limited amount of time (time estimations for all measuring tools are given in appendix 8.5.3.2). It only requires computer work and has no significant risks that can obstruct the process of measuring. Since the data is delivered by the BCEs, it does not affect the biodigester owners in any way. No costs (which are estimated for all measuring tools in appendix 8.5.3.1) are involved.

	Simple	Risks	Intervention	Affordability	Time
KBP database	5	5	5	5	5

Table 12: process scores for KBP database.

4.1.2 Evaluation of user survey

Performing surveys does not require any pre-measuring efforts, except for printing and a number of logistic preparations to visit the households. The logistics of the fieldwork are the major factor that limits the number of potential visits to households, as explained in appendix 8.4.3.

The process of performing surveys went without particular problems. Of the eleven biodigesters, ten surveys were performed, of which seven were fully filled in by the respondents. One household seemed to be bothered by the whole process and was skipped, since the survey requires another meeting with the responsible household member. For the three showroom plants, the data was partially estimated, since there was no household to interview and the company staff is not an objective source for neutral product information. In most of the cases the owner was the person responding to the survey questions. In some cases it was the partner or son of the owner.

None of the respondents appeared to be illiterate. Although all respondents managed to answer all questions of the survey, it seemed that the questions were sometimes quite complex for the respondents. Even with assistance it took quite some time to read and answers the questions. It remains unclear whether the respondents are able to deliver correct answers when no assistance is provided or nobody checks the answers on mistakes. Another point of concern is the ordinal scale that was used for answering certain questions, which seemed to be disturbing to the respondents, as explained by appendix 8.4.1.1.

Processing of the survey data is a simple process and does not lead to any difficulties. There were no problems with reading different handwritings. The questions with scale answers were analysed in excel.

4.1.2.1 *Key findings*

An overview of the process scores is provided by Table 13. Performing surveys as a measuring tool is relatively easy to organize. Logistics seem the main effort and costs of performing a survey. Beside that it is a rather time extensive and cheap measuring tool. When calling the household in advance the risk of failure is low. It requires a visit to the household, but since it is just a single visit the level of intervention is limited.

	Simple	Intervention	Affordability	Time
User survey	4	3	3	3

Table 13: Process scores for user survey.

Keeping the questions simple without any scale variables is recommended. Informing the households on the visit in advance and interviewing the person that has the most extensive knowledge about the biodigester also increases the success rate.

4.1.3 Evaluation of logbooks

Experiences show that households have different interpretations and use other methods for filling in the logbook. Although there is a proper and simple instruction manual in Swahili and English in the back, most of the responsible persons did not take the initiative to read the instructions well.

It is sometimes problematic that more than one person takes the responsibility and that the owner is usually not one of them. The owner of the plant is mostly the oldest man of the household and the person that is in charge of cooking is mostly the wife of the owner, a housekeeper or one of the daughters. The person in charge of the feeding of the biodigester is sometimes the owner, but often the son of the owner or the servant of the farm. This issue sometimes led to different methods of filling in the logbook, for instance for the estimation of stove intensity. This can be seen through the name of the person that made the note.

Beside printing the logbooks and logistics this measuring tool does not require other pre-measuring efforts.

Most households took proper records and were engaged in the process. They took the recording serious and payed more attention to their cooking and feeding behaviour. Most households did not directly ask for rewards. In the case of one household a reward was demanded for the farm servant who took the records. The majority did not state a clear demand. Most, however, did ask whether there was any token available for their efforts. During the fieldwork it was decided that providing any form of reward would be reasonable. Most of the responsible persons received the borrowed weighting scale as token. Some others received an amount of money of about ten dollars as reward.

Survey data was analysed in excel in order to produce graphs and compare the results with the data logger results. Entering the data was slightly more time consuming than processing the data of the survey, since all daily records needed to be filled in the excel sheets of the data logger data manually.

4.1.3.1 *Key findings*

An overview of the process scores is provided by Table 14. Since the owners were visited at least twice to apply the logbook as a measuring tool, time and financial requirements, due to logistics, were twice these of the survey. It is, however, not a complex level of organizing, except for contacting and instructing the respondent in advance. The rate of intervention, however, is very high, since the persons have to mind multiple times a day about the records.

	Simple	Intervention	Affordability	Time
Logbook	4	1	2	2

Table 14: process scores for logbook.

It became evident that good face-to-face explanation of the logbook method to all of persons involved in filling in the logbook, either for cooking or for feeding, is essential.

4.1.4 Evaluation of data logger

Installing the data logger comes with a number of challenges and problems. First of all, there are has quite some transport requirements, because of the size of the device and the number of visits.

Connecting the data logger requires cutting of the biogas piping. The assistance of a biogas entrepreneur or technician is required for this, at least twice. After connection the data logger all connections of the piping of the datalogger must be tested for leakage. Leakage was detected during the installations multiple times, demanding additional visits in some cases. In one case, it took a number of hours and only replacing certain tubes solved the problem after a second visit. Beside leakage the hosepipes are required to connect the data logger with the piping. These were often weak leading to kinking, which affects the pressure at the stove. With some improvised tools such as duct tape the hosepipes had to be reinforced to reduce the kinking. For one data logger the connection pipe to the pressure sensor was broken and had to be repaired in an improvised way.

During the installation of the data logger, the selection of a suitable spot sometimes appeared to be problematic. Three variables need to be taken into account:

- Distance to the expansion chamber for the temperature sensor (< 5 meter);
- Placing of the data logger close to the piping (< 1 meter);
- Distance to a suitable spot for the installation of the solar panel and battery box (< 10 m).

Other factors also play a role, such as the availability of a structure to mount the data logger, the presence of cattle and the risk of theft. These all reduce the options for installations, resulting in e.g. no installation of the temperature sensor.

During a number of the fieldwork sessions there was no data written by the data logger, although the device was installed correctly. This was due to a number of causes:

- There were problems with the power connections. One solar panels was covered in dust, a number of batteries needed to be replaced and one cable was interrupted.
- There was a problem with the newly purchased flash disks that apparently needed to be formatted in a certain extension.
- Three temperature sensor connections or cables broke
- There was at least one seriously malfunctioning flow meter that did not record a flow for a certain period due to an unknown failure.

Because of these issues the households had to be visited a number of times to make sure that useful records were taken.

Time records were made of the moments of inserting and ejecting the flash disk, for the purpose of time calibration. The names of the CSV files data loggers, which were supposed to represent the corresponding date, where all listed with varying file names, in most cases not representing the correct dates and none representing correct times. It was a time-consuming and insecure process to create a chronological well-connected datasheet from the separate .CSV files without any interruptions.

The high amount of data strongly reduces the overview of the excel sheets. Note that the number of rows in excel amount 1440 for one day, 10080 for one week and 43200 for one month. Due to the amount of data it is hard to detect missing data, it takes a lot of time to produce proper graphs.

4.1.4.1 *Key findings*

An overview of the process scores is provided by Table 15. The data logger is a lot more complicated tool than measuring tools like surveys and logbooks. Installing, operating and retrieving data are all complex phases with series of risks that can disturb the process of producing useful results. Many problems were reported and although many of them can be solved. Although most problems were solved, it needs to be considered that there are many factors that can disturb the research process.

The process requires check-ups every few weeks and a significant period of data analysis, making it a time consuming process. Even when the purchase costs of the data loggers in 2014 are excluded, the required logistic costs for the installation are high.

	Simple	Intervention	Affordability	Time
Data logger	1	1	1	1

Table 15: process scores for data logger.

Advisable for using the data logger is that the measuring protocol that is developed for ABPP is used when a measuring study is done. That the household is informed well about the purpose, the functioning and the neutrality of the study, and that someone is hired that can help locate homes.

An important remark is that the 1 minute data does not seem to have any advantages to 5-minute or even 10-minute data. In none of the data analysis minute-specific data created any new opportunities in observations.

4.1.5 Evaluation of visual observation

In general, preparations for visual observation does not require a lot of effort, beside logistics and informing the household. Visual observation however seemed to require a good explanation to the household representatives. Explaining the aim of the study, emphasizing the neutrality and also connecting socially with the household members is no hard science but seems to be essential. For instance to get permanent access to the kitchen to observe the stove and to get all the information from the household representatives.

Some types of visual observation do not require any difficulties, such as observing the wear and tear of the digester. Others require more time and explanation to the household members, such as visual observation of stove use. Furthermore, visual observation could be time consuming, depending on whether the research plan fits with the activities of the household. For instance, when the desired observation is feeding, it depends on the decision of the household when the feeding takes place and thus how much time is required. For observing the wear and tear of the biodigester it only requires the permission of the household to enter their property when they are not around, making it more probable that it is less time consuming. The time requirements also depend a lot on the amount of desired data: observing one cooking session probably takes a maximum of a couple of hours waiting plus the observation time but observing the cooking behaviour during one day probably requires the whole day.

Another problem with using visual observation as a measuring tool is that the obtained data is sometimes vague. It is for instance challenging to translate an observation of a flame into a comparative measure that describes the stove pressure and can be compared to results of other field work sessions. This shows that visual observation is rather a method of checking the data obtained by other measuring tools than an independent tool.

4.1.5.1 *Key findings*

Visual observation is a simple way of analysing data, since the preparations are limited and it only consists of observing. For some types of observation the decisions of the household must be taken into account. Observing the cooking of the household relies on the plans of the households and when they do not plan to cook it might change the observation. Observation also seems to be a quite personal activity, which can intervene in the privacy of the household, although this has not been assumed to be necessarily problematic. Visual observation can obtain good insights within a short time period.

	Simple	Intervention	Affordability	Time
Visual observation	4	1	3	2

Table 16: process scores for visual observation.

It became clear that the time that is required for a visual observation depends a lot on whether the plans and desires are matched with the program of the household before visiting.

4.2 Data quality assessment

The quality of the data was analysed for every performance indicator per measuring tool. The results are given in this section. Also, the usuability of the measures that were proposed are discussed.

Note that the full data sheets obtained from the logbooks and data loggers are given in appendix 8.7.

4.2.1 Dung input (Specific Gas production & stability of gas production)

For determining the specific gas production, both the input of dung and the production of gas needs to be measured, which was done using the logbook and visual observation.

4.2.1.1 *Quality of feeding records logbook*

The logbook show proper records on dung input. All households finished their records until the last day of the logbook. All households either gave an indication of the mass of one full bucket or added up the weight of all buckets on daily basis.

The completeness of the feeding records is hard to detect, since the data logger does not provide reliable information on this. Most logbook records however show one daily record of feeding around a standard time on the day. In communication with the household became clear that double or triple feeding is both rare. The households with irregular records (feeding skipped for one or more days) the irregularity of the feeding was confirmed by the responsible persons.

Visual observation for the feeding behaviour of all household appeared to be a highly time consuming approach. Every household uses different feeding times, making it hard to plan the visits to the households. For some households, the feeding was observed in order to check whether the household's estimations of dung input listed in the logbook is representative for the reality. This method can be a check-up for the logbook, but is not desired as an individual measuring tool.

4.2.1.2 *Comparison of tools*

In three cases, the first weighting session of the dung by responsible person were observed. Due to inattention to the calibration of the scales or inexact measuring, the mass recorded did not always exactly match the measured mass. One time, the measuring of the same bucket had been repeated a number of times to be sure. In that case, the records varied with up to 2 kilograms from each bucket of around 20 kilograms, which means an inaccuracy of around 10%.

Household name	Mass of bucket by household	Visual observation	Variation
2. Mutwiri	20	18 (*a)	-10% (*a)
7. Unkown	22	20	-10%
8. Mari	20	20	+/- 0%
(*a) The household cleaned the dung first with additional water and flushed the liquid part through the irrigation canal, wasting part of the mass. This dung input measured by visual observation is an estimation.			

Table 17: results from visual observation that show the precision of weighting by households and the error margin.

4.2.1.3 *Measures for dung input*

As described in the method section only one measure for dung input was proposed, which is the input of kg raw dung per day. There is no observation that has led to a better alternative. However, a number problems with the definition of dung became clear during field observations.

First of all the dung of the household of biodigester 1 appeared to have a very high moisture content in comparison to other observations. This is probably due to the fact that the stables are cleaned with water, which irrigates the dung to the stockpile for the biodigester. This was not included in the water input in the logbook. Another irregularity was the feeding of household 4, who first cleaned the dung with water and only flushed the more solid part in the digester. Checking the way of feeding by visual observation can be a solution.

4.2.1.4 *Key findings*

Data quality results are presented in Table 18. Visual observations of the feeding and communication with the households show that the feeding records are assumed to be very complete and quite accurate. Visual observation is even more accurate but lacks completeness, since only one observation is done that might not be representative.

Dung input	Accuracy	Completeness
Logbook	4	5
Visual observation	5	2

Table 18: data quality results from two measuring tools for dung input.

It is advisable to mind the fact that the selected households do not have any addition of water to the dung before the mixing process, in order to make the different records as comparative as possible.

4.2.2 Gas flow (specific Gas production)

The other part of data collection required for determining the specific gas production performance is the gas flow. This can be done by data logger or estimated by logbook. Also, visual observation was used to check the two other measuring tools for errors.

4.2.2.1 *Quality of flow records logbook*

Comparing the data logger records (example given by Figure 12) with logbook records show that in general most households are able to make accurate records of their gas consumption. In some cases, almost all sessions of gas consumption are recorded, for example in the case of biodigester 5.

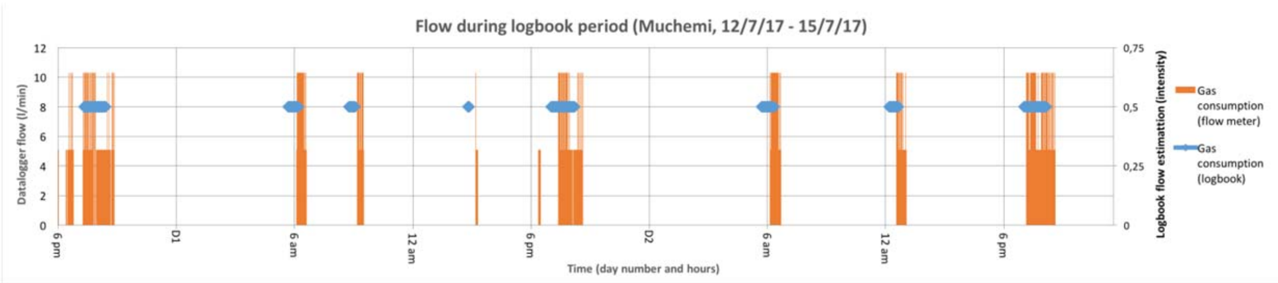

Figure 12: example of successful gas consumption records from logbook combined with flow meter data.

Other logbook records show a lot of missing values or inaccurate starting times. An example is the case of biodigester 9 (Figure 13). The logbook was not complete enough to represent the gas consumption of the household.

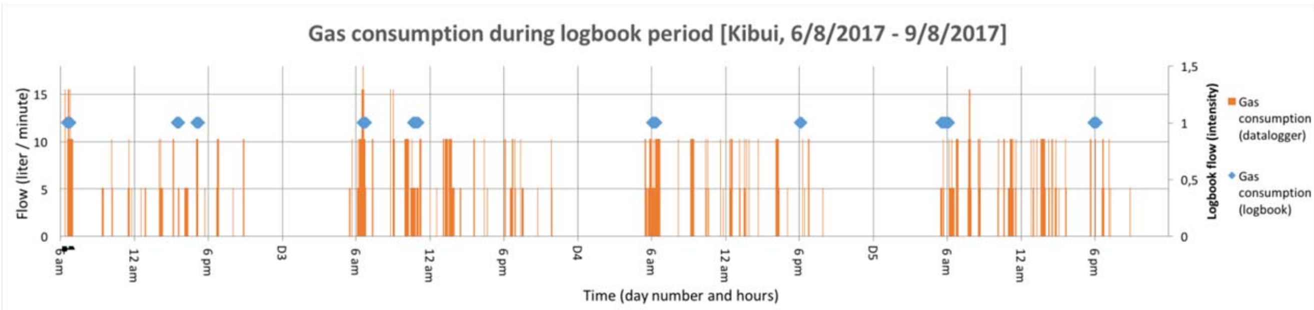

Figure 13: example of unsuccessful gas consumption records from logbook combined with flow meter data

4.2.2.2 *Quality of notes from visual observation*

Two stove visual observation sessions were done, both to observe whether the flow meter records all flows and to check whether the dynamics in flow are the result of changes in the position of the stove button. During the last day of the field work session at the biodigester of plant 6 a cooking sessions were observed. For plant 8 the same was done in an experimental setting without cooking purposes.

Furthermore, visual observation provided new insights in the functioning of the other measuring tools in the field of gas production. It was observed that a flow is not able to pass when the pressure of the biodigester drops below a certain level. Apparently, the resistance of the diaphragm type gas meter and the internal piping of the data logger is too high and cooking needs a minimum pressure of at least 1.5 – 2.0 cm H2O when the data logger is connected, and otherwise the flow is obstructed.

4.2.2.3 *Quality of flow records data logger*

Comparing the flow data with the records from the visual observation provides insight in the reliability of the flow meter. The results given in Figure 14 show that the data logger reacts quite accurately on the changes in the position of the stove button, indicating that the dynamics of the flow meter follow the expected path.

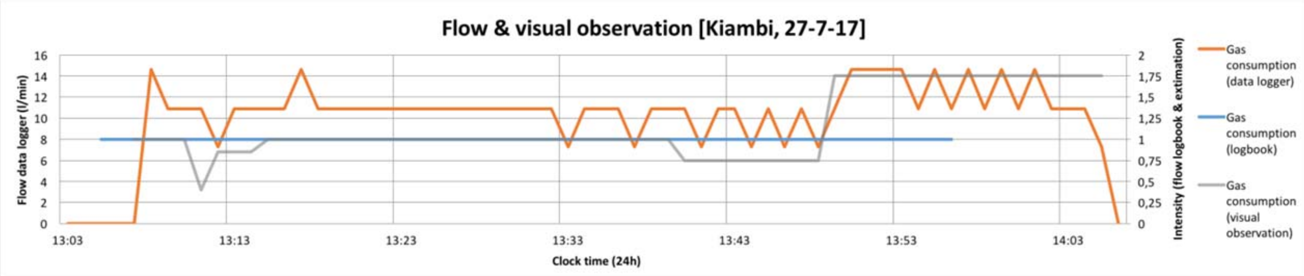

Figure 14: line graph showing three different ways of measuring the gas flow.

One issue for finding a proper flow meter for biogas measuring purposes is that certain biogas devices (e.g. biogas lamps, milk chillers) operate under low pressures and that some flow meters require a minimum flow to record. Results at the biodigester of household 8 show that the ABPP flow meter is able to detect the gas consumption of a *Biogas Milk Chiller* made by Simgas. As visualized by Figure 15 there is an obvious difference in consumption pattern that occurs around 4:15 pm. A baseload consumption of 39 liters per hour, which matches the estimation of Simgas of 40 liters per hour. Also, a clear difference is observed between the consumption of the milk chiller and the rate of consumption of regular cooking, which amounts 678 liters per hour for the cooking period of Figure 15.

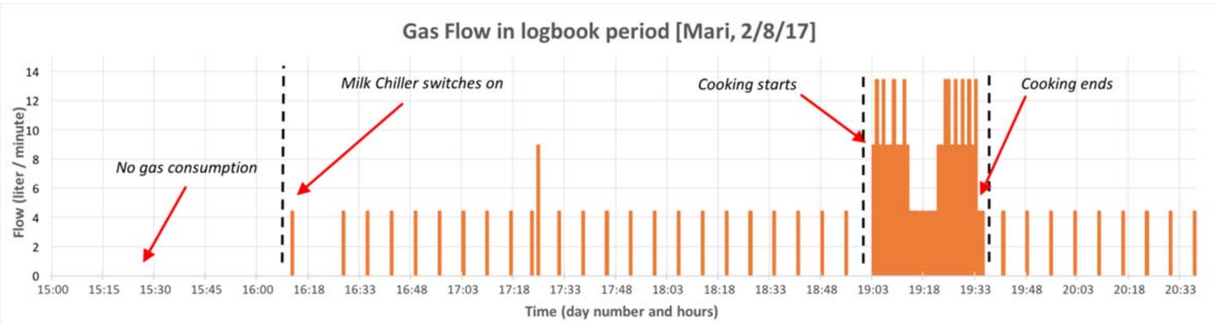

Figure 15: gas consumption record showing the record of Milk Chiller in the flow data.

The data logger is only able to show a limited number of magnitudes. In the case of the data logger installed at biodigester 6 (Figure 14) the recorded flow is always a product of 3.6, which is due to the recalibration of these old flow meters. In the case of the data logger installed of biodigester 12 (data logger 1 in Figure 16) it is always a product of 5.1. This is due to the fact that the flow meter is an analogue meter with a digital sensor that only records one or half of a rotation. Flows in between these numbers are indicated by a fluctuation of the numbers around that can be recorded. When the meter is calibrated on 4 liter per rotation, a flow of 7 liters per minute will be recorded as three records of an 8, and one records of 4 liters per minute.

A test was done in order to check whether the calibration of the flow meters is still correct. Two data loggers were placed in series while taking records of the flow of the Blueflame biodigester. The installation of the two data loggers in series at the Blueflame biodigester provided insight in the expected accuracy of the flow records of the flow meter. The flow graphs show that there is a significant difference between the records of the first and the second data logger, which is visualized by Figure 16.

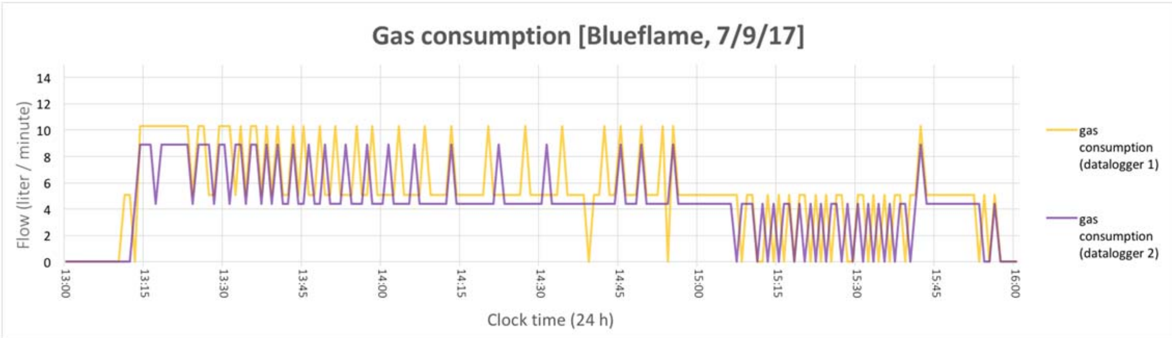

Figure 16: flow records of the two data loggers in series at the Blueflame biodigester.

The variation seems to be equal over time and it is a fixed percentage, instead of an absolute value. Three cooking sessions took place during the measuring period, of which all records show higher values for the first data logger in comparison to the second. The second one showed for all observations a value between 14% and 15% lower than those of the first data logger. Since no similar experiments were performed it is hard to estimate whether this is occasional. However, a wider error margin should be taken into account.

An alternative explanation is the assumption that the difference is created by the internal pressure drop inside the first data logger system, due to internal resistance. Pressure drop leads to expansion of gas and thereby resulting in records manipulated by the flow meter. This explanation can be rejected by doing a brief calculation using the ideal gas law that is described in appendix 8.6.2.2.

4.2.2.4 *Measures for gas consumption*

Monitoring the total consumed gas by the sum of the flow records seems to be a useful method of measuring the total gas flow.

Multiplying the intensity indications from the logbook with the cooking time for every cooking session provides an expression of flow that was assumed to be a proper representation of reality. Assuming that beside some calibration issues the flow of the data logger is quite accurate, a scatter plot was made to see whether the intensity-hours per cooking sessions correlate with the flow measured by the flow meter. Because many of the logbooks showed missing data points it was chosen to analyse the regression with a household that kept proper logbook records without many missing data points. Flows for missing logbook values or logbook records without any recorded flow have therefore been excluded.

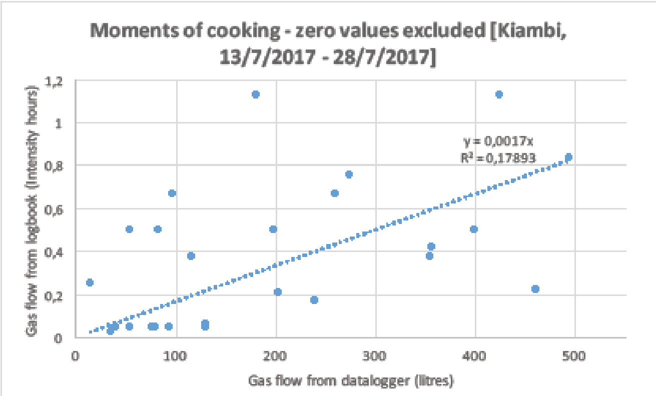

Figure 17: scatter plot showing regression between two approaches of measuring the total flow of cooking moments.

Figure 17 shows that there is a correlation between the gas flow estimated from the logbook data and the gas flow measured by the data logger, but the data points diverge highly from the average regression. A calibration factor of 0.0017 intensity hours per liter (or 1.7 intensity hours per m3). An R^2 of 0.18 is given, which means that just a small part of the total variation can be explained by this regression. Hence, measuring the flow by intensity-hours is not adequate.

The results presented in Figure 18 show the cooking times retrieved from the survey, logbook and data logger. Since the data logger can be assumed to be the most accurate measuring tool it seems that the logbook records provide an accurate impression for only three out of eight of the observations. The survey barely seems to be representative for the cooking time that the biodigester provides. Both the survey and the logbook cannot be considered as adequate for estimating cooking time.

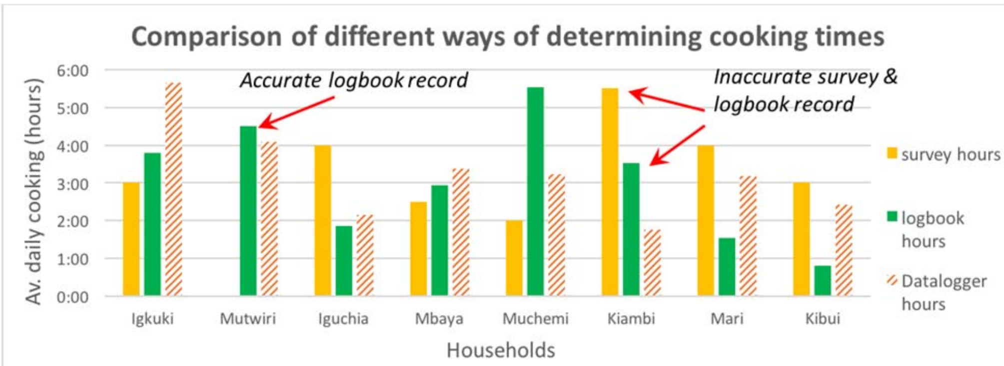

Figure 18: bar diagram visualizing the variance in observations of cooking time between three methods of determining.

Regression between the cooking time and total flow that are both derived from the data logger show that 80% of the variation in daily flow is explained by the variation in cooking time. Cooking time is a good indication for the expected gas flow, but the regression, which is presented by Figure 19, is not strong enough to estimate the gas flow by cooking time quantitatively.

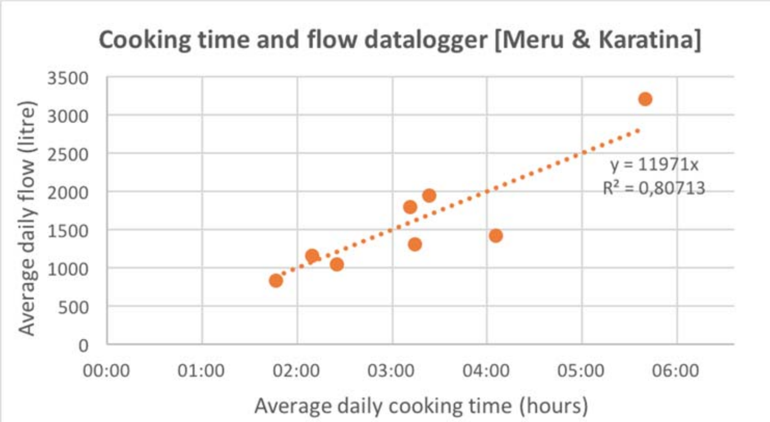

Figure 19: scatter plot showing regression between the cooking time and total flow of the data loggers from the field study in Meru & Karatina.

4.2.2.5 Measures for specific gas production

Taking into account the findings from 4.2.1.3 and 4.2.2.4 show that the logbook records of unmixed dung feeding in comparison with the summed-up flow records from the data logger are the most accurate approach of calculating the specific gas production (SGP). The values were calculated for the logbook period of all household-owned digesters in Kenya, of which the results are given in Table 19.

Household	1	2	3	4	5	6	8	9
N (days)	4	5	7	7	2	7	7	7
Dung (kg)	400	560	273	700	80	285	525	230
Gas (liters)	14,475	5,697	8,721	14,485	2,296	6,164	13,096	8,148
SGP (l / kg)	36.2	10.2	31.9	20.7	28.7	21.6	24.9	35.4

Table 19: calculation of specific gas production (SGP) during the logbook periods of the biodigesters from the Meru and Karatina fieldwork sessions.

Values between 10 and 35 liters of gas produced per kilogram of dung input were observed out of eight observations. Most of these observations seem to be quite high (usually between 8 and 26 liters per kg [8]), but realistic. Note that the estimated inaccuracy of the dung input is 10% in general and for the flow data approximately 15% between different data loggers. In total an inaccuracy of roughly 25% must be considered as plausible.

4.2.2.6 Key findings

The logbook records of the gas production seem to be proper indications that can be used for checking the data logger flow data on calibration issues and explain certain flows. Approaching the consumed gas volume by logbook is however quite inaccurate and not always complete enough. The survey and visual observation are not useful for any estimation of the consumed volume. The flow meter is however quite accurate and is suitable to measure the gas production of a period of a number of weeks or months.

Gas production	Accuracy	Completeness
Survey	1	1

Logbook	2	3
Data logger	4	5
Visual observation	1	1

Table 20: data quality scores of different measuring tools for gas production.

The combination of logbooks for the estimation of feeding of dung and the summed-up flow figures of the data loggers appears to be good estimation of the relative gas production. However, it still has an significant expected inaccuracy. Visual observation seems to be good for improvised qualitative observations but not to be a thorough method for quantitative gas production data, since it requires a long time of observation and the results are arbitrary.

4.2.3 Gas pressure

The gas pressure was recorded by the pressure sensor of the data logger, by three survey questions and by visual observation.

4.2.3.1 *Raw data*

The pressure sensor of the data logger gives a useful insight in the digester gas volume. The data is processed by the same data reading file that is used for the other data obtained by the data logger. Pressures go up 100 cm H2O for the brick dome types, 80 cm H2O for the Simgas types, 9 cm H2O for the Blueflame and 4 cm H2O for the Rehau types. The data is given with a precision of 0,1 cm H2O, which means 0.1% of the maximum pressure of a brick dome type and 2.5% of the maximum Rehau digester pressure.

Changes in pressure furthermore relate closely to the records from the flow meter. There is a steady increase in pressure (around 2 cm H2O per hour, Figure 20) during moments of no flow and sharp decrease of pressure (around 10 cm H2O per hour) during moments of gas use of biodigester 5. Most of the household start cooking early in the morning and have substantial gas use during the day time until around 21 pm. Hence, the gas pressure especially increases overnight and is generally higher in the morning than in the evening.

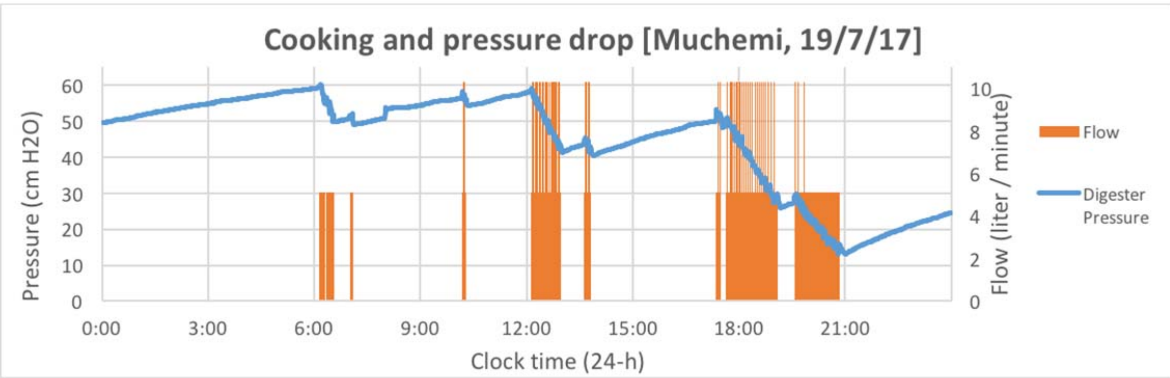

Figure 20: the effect of gas consumption on the pressure record.

The survey show results of digester pre-cooking pressures of 50 to 140 cm H2O. A number of digesters is not equipped with a pressure gauge. In these cases the pressure could not be estimated. Most households indicate that the pressure is never too low to cook. The pressure of the Blueflame and Rehau digester was estimated, because the digesters are not owned and used by households. The flame of these digesters was not always able to sustain the influence of the wind. The fact that these digesters were still in the start-up phase after a longer time of inactivity also plays a role. The satisfaction rates for the gas pressure was rather high for most of the households.

Visual observation showed that most of the observed brick-dome and Simgas plants (first two flames of Figure 21 from the left) had gas pressures without any reduced cooking convenience. However, in a few cases the pressure (flame quality) was moderate or dropped quickly during cooking. The Blueflame and Rehau (right flame of Figure 21) digesters clearly showed weaker flames.

Figure 21: visual observation of the pressure of respectively a brick-dome digester (biodigester 6) a Simgas digester (biodigester 8) and a Rehau digester (biodigester 12), through the observation of flame strength. Pictures from personal archieve.

4.2.3.2 *Accuracy of pressure sensor*

Although the pressure sensor seems to give an accurate insight in the developments of the biodigester a number of events can disturb the records.

First, for some digester systems it is usual to close the main valve during the times of the day that the gas is not used. This led to manipulation of the results of the Blueflame biodigester. The data logger was placed after the main valve, which was closed the majority of the time. Only three days before the end of the measuring study this was discovered and the instructions were given to keep the main valve open for 24 hours per day. In the pressure record this can be observed in the sudden increase from 1 to 6 cm H_2O between day 8 and 9.

Second, the pressure sensor seemed to have a standard bias. During a pre-pilot a standard bias of plus 0.3 – 0.6 was measured for all data loggers. In later records the standard pressure appeared to be zero. Figure 22 was recorded at the moment when the data logger was connected and shows some moments where the data logger was connected and unconnected. It becomes clear that the standard bias of the pressure sensor is a negligible and influences the pressure record of the brick dome type for up to 1% of its average pressure.

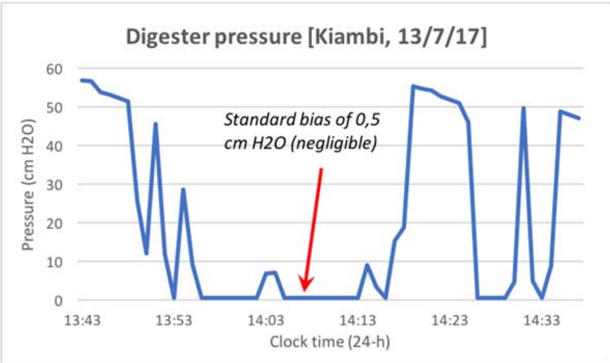

Figure 22: effect of standard bias on temperature record.

For low-pressure digesters, this becomes however more problematic. The standard bias can equal 20% of the maximum digester pressure and can be higher than the post-cooking pressure in the digester. This is an inaccuracy for the low-pressure digesters. Another observation is that the records of digesters with high pressures are much more stable and low-pressure digesters fluctuate more. It seems that at pressures lower than 5 cm H_2O the differences become too marginal to measure the absolute values in an accurate way. This is also confirmed by the manufacturer. The rough trends in pressure development is however still visible.

During the series observation of the Blueflame digester, a difference in pressure was detected between the two data loggers (Figure 23). This variation seems to be greater when the absolute pressure is higher. With a pressure of around 6.9 cm H2O for the first data logger, the second shows a pressure of 6.2 cm H2O for the low, both under stable conditions with an assumed equilibrium between gas flow and pressure within the piping. Under lower pressure this variation is lower in absolute terms. The variation seems to be 10% of the total pressure, which is quite a wide bandwidth that needs to be taken into account.

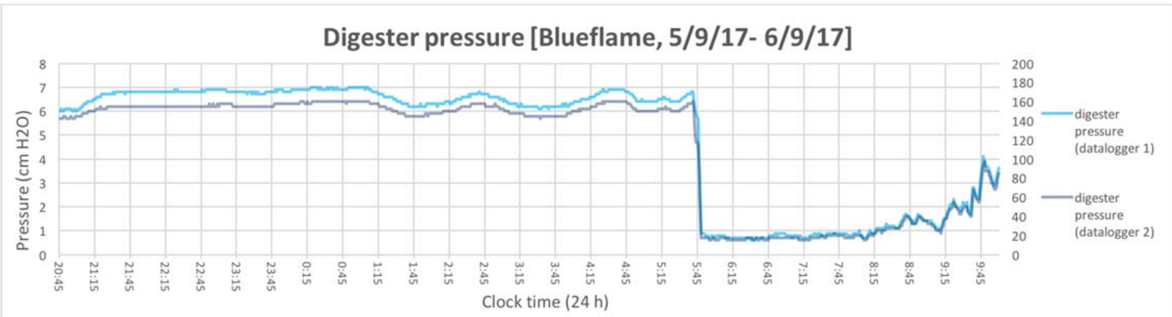

Figure 23: pressure records of the two data loggers in series at the Blueflame biodigester.

A fourth issue is the drop of pressure that occurs in certain systems while cooking, as visualized in multiple short cooking events by Figure 24. A part of this pressure drop is representative to the decrease of pressure in the digester, but another part is caused by the pressure loss within the data logger. This drop is directly compensated in the first minutes after cooking. For some data loggers, it occurs and it probably depends on the extent of kinking in the piping. For the overall-picture the pressure drop is not problematic, but it gives a false impression of the pressure during gas consumption.

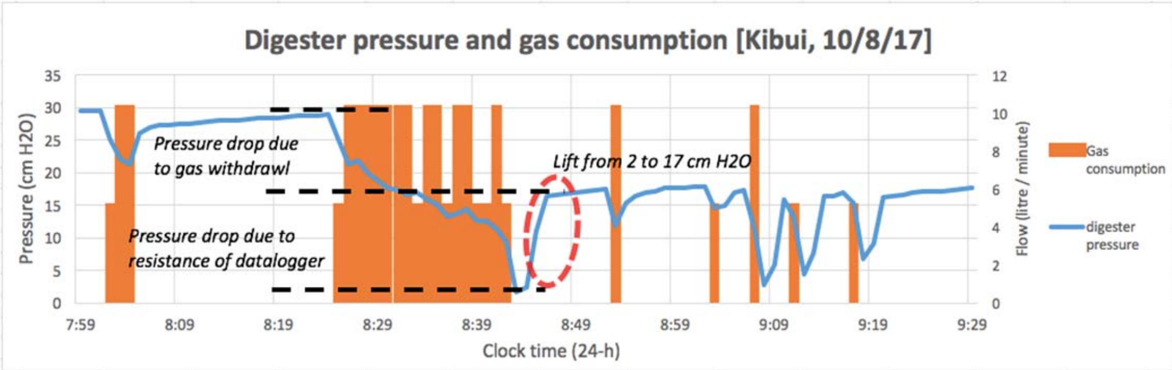

Figure 24: Pressure drop during cooking.

For digester 10 and 11 (Rehau bag-types) pressure is artificially created by placing a ballast on the gas storage, which becomes clear in Figure 25. Usually the pressure of this digester itself does not exceed 3 cm H_2O, but the pre-cooking pressure often reaches triple in a short time period before cooking.

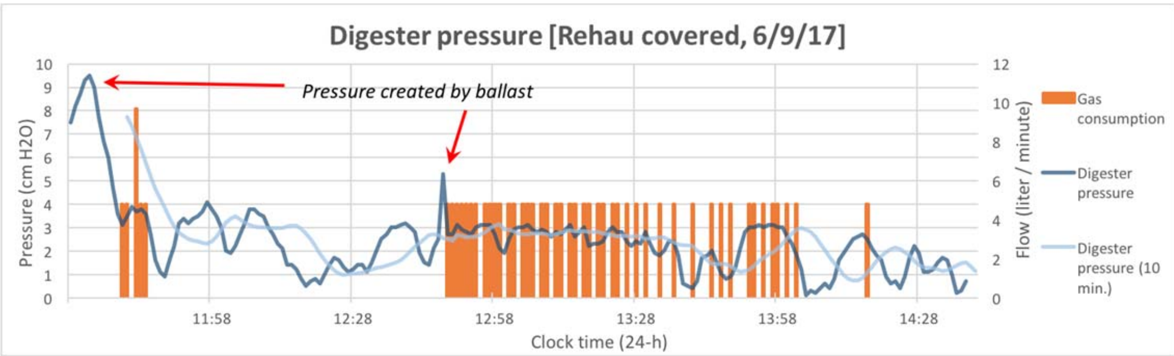

Figure 25: pressure of Rehau digester during a cooking event. The high fluctuations of the pressure data under low pressures become visible.

Note that weather events do not affect the pressure records [37].

4.2.3.3 *Accuracy of visual observation*

Determining the pressure by visual observation of the flame does not seem to be an accurate way of estimating the performance of a digester in this field. First of all, the quality and shape of the flame was often affected by the type of the stove, of which some required maintenance. Another point of concern is the fact that the gas pressure and the flame strongly depend on the moment of the day. Households that were visited in the morning experienced higher flame intensities and pressures that the households visited in the evening. Overall, it seems to be difficult to rate the pressure by stove performance.

4.2.3.4 *Measures for pressure*

Average pressure can be used as a measure for pressures. The issue with using average pressure as measure seems to be that people with higher gas consumption withdraw more gas and have on average lower pressures. Also, the pressure of some digesters (e.g. Rehau) can be artificially enlarged, for instance by placing a weight on the gas storage volume, overrestimating the useful gas pressure.

Because of the fact that a number of households did not lead to complete surveys and that some biodigesters systems did not have a pressure gauge there were only six households with complete data for comparing the survey outcomes with the data obtained from the data logger. Among them were four brick-dome digesters and two Simgas digesters. The observed pre-cooking pressure ranges from 4 to 10 kPa . Per household the range had a maximum of 4 kPa between the lowest and highest value.

In four out of ten answers from the survey the pre-cooking pressure was indicated to be at least 2 kPa higher than the highest pre-cooking pressure measured by the data logger. In the case of the household of biodigester 1, the indicated pressure was even more than 6 kPa overestimated. In contrast the pre-cooking pressure indicated by the households biodigester 3 and 6 were accurate and in the middle of the range derived from the data logger. The results presented by Figure 26 show that estimations of the usual pressure before cooking done by the households have a high probability to be inaccurate. It is likely that also the survey indications of post-cooking pressure are inaccurate.

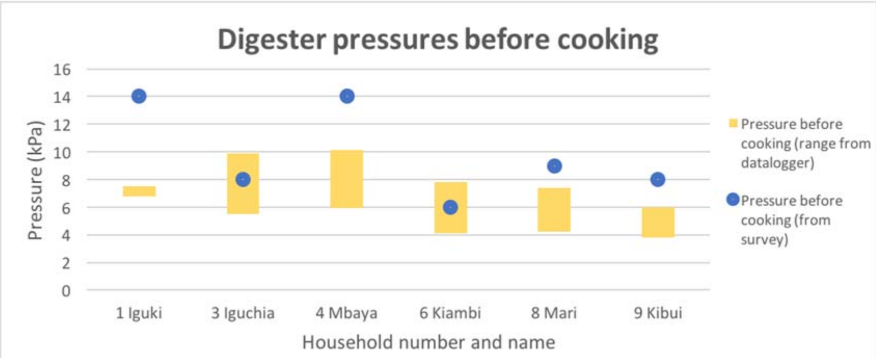

Figure 26: comparison of pre-cooking pressure determined by logbooks and dataloggers.

In addition, the satisfaction rate and frequency of low pressure of the household was monitored by survey Table 21. Since the households do not critisize the biogas technology easily (as explained in appendix 8.4.1.2), the method did not seem to be promising.

Household	Gas pressure before cooking (survey)	Gas pressure before cooking (data logger)	Satisfaction with average gas pressure (survey)	Frequency of low pressure (survey)
#	kPa	kPa	1 (no) to 5 (yes)	1 (never) to 5 (often)
1	14	6.8 – 7.5	5	1
2	n/a	5.0 – 7.9	n/a	n/a
3	8	5.5 – 9.9	5	1

4	14	5.9 – 10.1	5	3
5	n/a [(b)]	4.2 – 6.7	5	1
6	6	4.1 – 7.8	3	1
8	9	4.2 – 7.4	5	1
9	8	3.8 – 6.0	5	4
(a) A number of biodigesters are showroom plants and thus the figures are not provided in this table. *(b) no pressure gauge present.*				

Table 21: comparison of different measures for explaining pressure performance.

Both pre- and post-cooking pressure seems to be a debatable measure. They both rely heavily on the cooking behaviour. Households that cook spread over the day are likely to have less extreme pressures than households that have one or few cooking moments. The variation between pressure profiles suggests that it is likely that the outcome of the measures is influenced by the cooking dynamics.

4.2.3.5 *Key findings*

Data quality scores for gas pressure are presented in Table 22. The approach of determining the pressure performance by survey is only suitable for indicating the rough indications of the pressure and the observations and risks not to provide the complete picture for the whole year. The completeness of the approach by visual observation is not more accurate and is highly biased by the moment of observation. When selecting a measure that is representative for the overall pressure the data logger is quit an accurate way of measuring pressure of brick dome type digesters, and indicative for the pressure of low-pressure digesters. Since the data logger is not very suitable for measuring during a whole year there can be a small bias.

Gas pressure	Accuracy	Completeness
Survey	3	3
Data logger	4	4
Visual observation	3	1

Table 22: data quality scores for gas pressure.

For the use of the data logger it is important to be aware which drops in pressure are representative for the digester pressure. Also the inaccuracy under low pressure must be taken in to account when analysing the results.

4.2.4 Stability of gas production

As described in the method section there are four aspects that can influence the stability of gas production significantly. Instable feeding, unbalanced feeding, low temperatures and strong temperature fluctuations. The data logger can be specific in these fields of stability, although the assistance of logbook is required in the field of stability related to dung input.

4.2.4.1 *Instability due to feeding*

The quality of the dung feeding records is described in section 4.2.1.1. Unfortunately, because of time limitations it was not possible to perform a study for more than a couple of weeks. Furthermore, since the logbooks seemed to be quite an effort for the respondents, it was not desired to take records for more than 10 days.

For monitoring the effect of feeding on the gas production stability requires records of a much longer period. Especially when the feeding of a household needs to be adapted to the research preferences. The experiences with digester 11 and 12 also showed that the start-up for an quasi- or non-operating biodigester is not a matter of one or a few weeks and probably requires more than one its own retention time in order to function stably and provide reliable results.

4.2.4.2 *Instability due to temperature*

As described in theory section 2.1, the gas production process of a biodigester can be disturbed by temperature fluctuations. Although these temperature fluctuations seem to be minor, the influence on accuracy seems to be abundant, because the temperature is specified with an accuracy of 0.1 °C. The adaption to the slurry temperature appeared that were measured seems to be a matter of a few minutes. It therefore seems to be an adequate way of monitoring the temperature dynamics. One difficulty is that the seasonal differences require a year-round measuring study, which is hard to perform due to the disadvantages of the data logger (described in section 4.1.4).

As the position of the data logger often depends on a number of factors, the options for inserting the temperature sensor is a matter of improvisation. For six of the seven brick-dome digesters the sensor was inserted through the expansion chamber into the outlet canal as close as possible to or in the digester volume. The recorded temperatures (Figure 27) appeared to be highly stable. For one brick dome the input canal was used. When these results were analysed it came out that the slurry temperature dynamics were about equal to the ambient temperatures, which means that the sensor probably was pulled out during feeding.

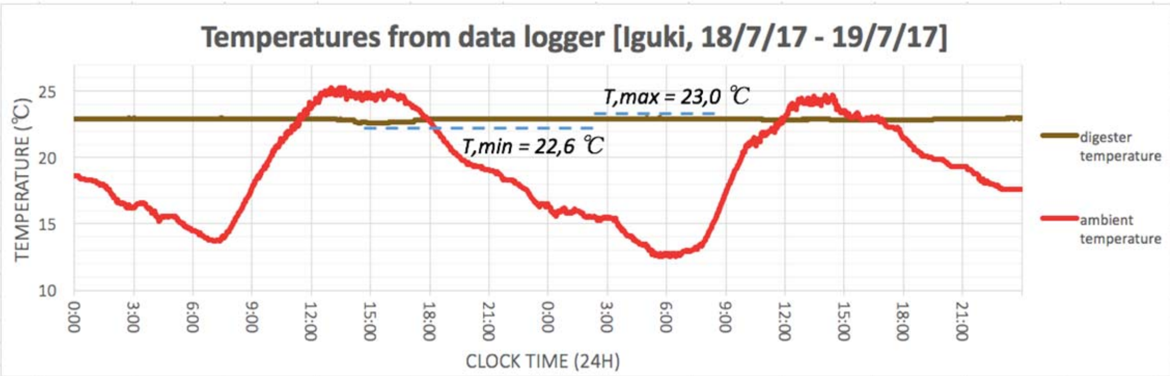

Figure 27: visualization of the temperature stability of a brick-dome biodigester.

The sensors of the Rehau digesters were also inserted via the inlet canal, but much deeper and fixed to a rod. The results (Figure 28) shows realistic figures of a more fluctuation temperature, but certainly due to the outside temperature, since the slurry temperature only rises during the hours that the ambient temperature is higher than the slurry temperature. It therefore does not seem to be affected by the feeding process. With deep insertion into the digester volume and the cable fixed to a holder, the method of using the inlet canal is optional.

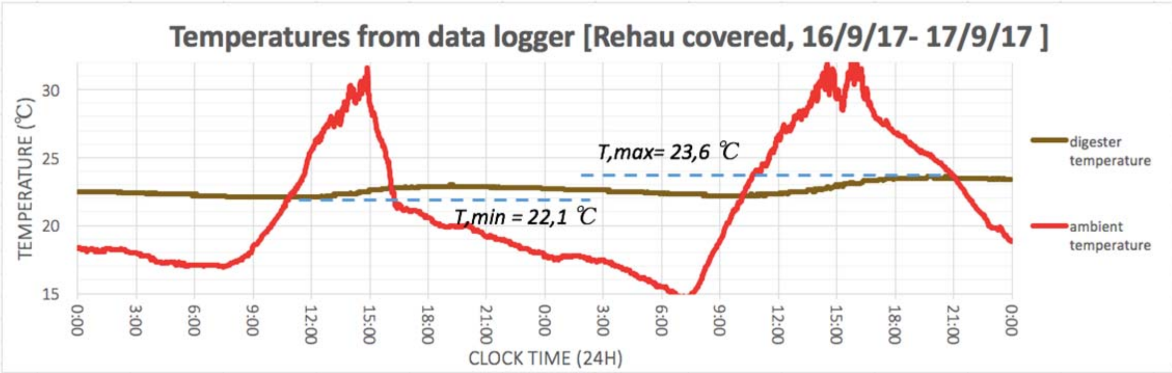

Figure 28: visualization of the temperature stability of a Rehau type biodigester.

For the Blueflame digester two temperature sensors were installed, one via the inlet canal almost reaching the digester and one via the open slot between the gas holder and the slurry tank into the digester. As visualized in figure (Figure 29) the results show a remarkable difference between the observations. The placing of the sensor seems to be determining for the reliability of the results. Moreover, it is unclear whether the slurry temperature could vary between different sides of the biodigester and mapping with different sensors would give a better insight in this.

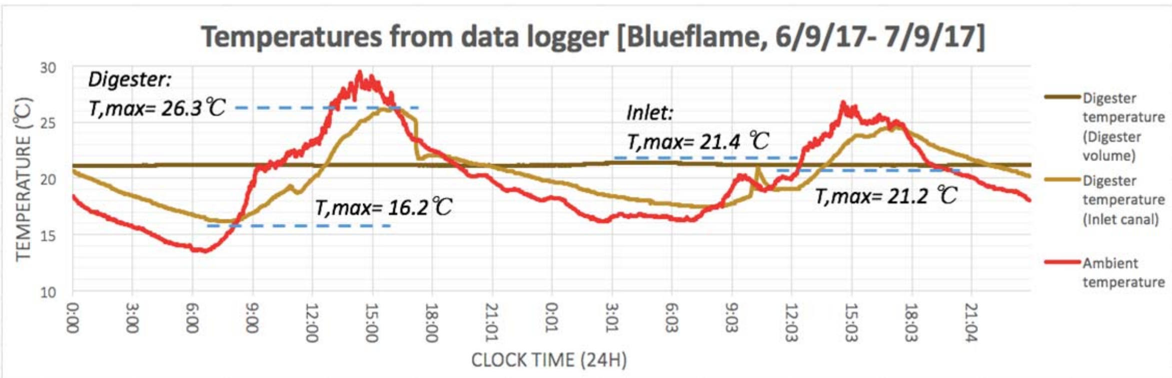

Figure 29: visualization of two ways of inserting the temperature sensor into the biodigester for slurry temperature fluctuation measuring.

Sudden fluctuations were observed in the digester temperatures that are unlikely to be the effect of the ambient air temperature. The fluctuations are presumably caused by the backflow of colder slurry from the expansion chamber because of gas withdrawal, as visualized by Figure 30. The slurry in the expansion chamber is in contact with the ambient air. When the that these fluctuations are recognized while analysing the results.

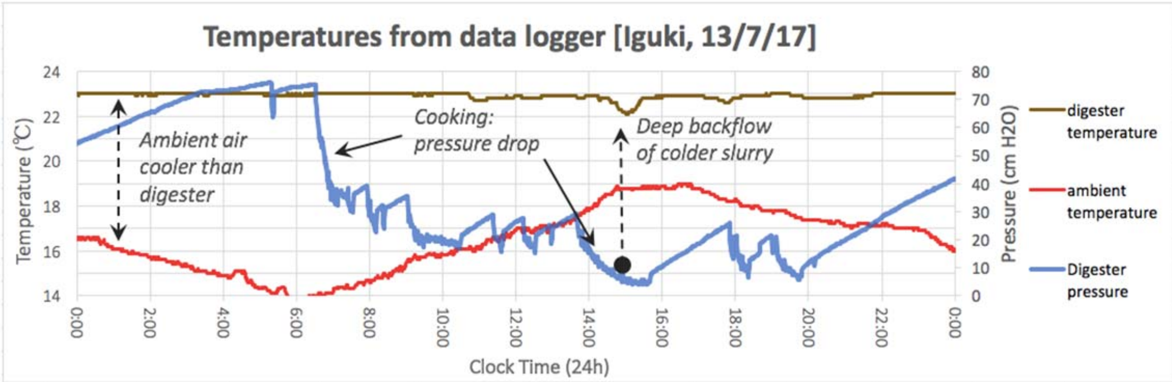

Figure 30: effect of backflow of slurry due to gas withdrawal on slurry temperature records via expansion chamber.

4.2.4.3 *Measures for instability due to feeding*

One way of monitoring the effect of unstable feeding is by rating the stability of the feeding by analysing the variance. A simpler way could be to rate the stability manually e.g. using a 1-5 scale. When the dung feeding is less or exceeds the advised feeding, it means that the feeding is unbalanced. A proposed way of expressing this is to measure the dung and water balance (explained and calculated in appendix 8.4.4). Taking the absolute values and plotting in a graph provide us an overview whether deviation from the advised feeding of dung or water lead to lower gas production.

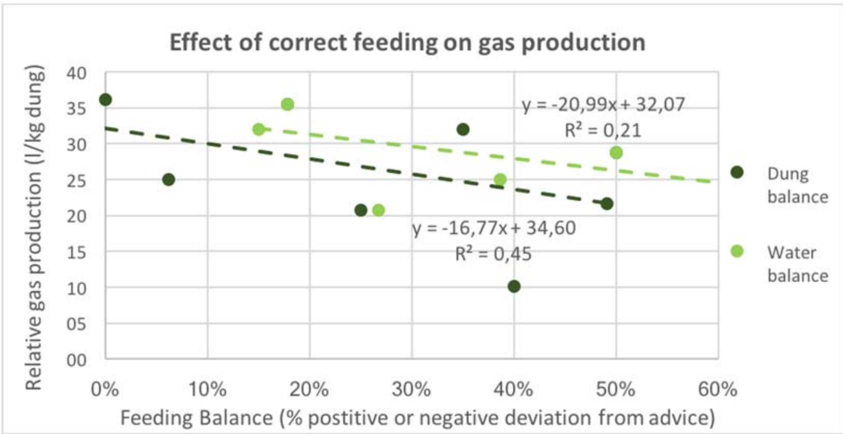

Figure 31: regression between dung and water balance of the logbook phase with relative gas production of the logbook phase.

Figure 32 shows that when the feeding deviates from the adviced amount, the relative gas production decreases significantly. The correlation is moderate for the balance per mass of raw dung, but only weak for the feeding of water. When the correlation for a certain digester type is low, it means that the performance is not very vulnerable to unbalanced feeding.

4.2.4.4 *Measures for stability due to temperature*

One proposed measure is to express the temperature fluctuation in the daily maximum difference in maximum and minimum slurry temperatures. The Blueflame (Figure 29) and brick-dome types (figure Figure 27) show very small fluctuation of respectively 0.2 and 0.4 °C. The Rehau digester (figure Figure 28) shows a daily fluctuation of 1.5 °C, which still seems marginal.

In extremer climates, the heat transport between the digester volume and the ambient air can increase, since heat transport depends on the temperature difference. It could be more reliable to relate the temperature fluctuations to the fluctuations of the ambient air temperature. This could however insufficient be tested, since the climates of the different fieldwork sessions are very similar.

The described measures all focus on one part of the stability of gas production. How to transfer this observation into a concrete measure remains unclear.

4.2.4.5 *Key findings*

By combining the feeding, temperature and gas consumption data the stability of the gas production regarding the feeding and temperature conditions can be determined. The data logger produces accurate and reliable temperature records, although the positioning of the sensor is a point of attention and the temperature fluctuations should be interpreted correctly.

Stability	Accuracy	Completeness
Data logger	5	3

Table 23: data quality ratings for stability of gas production.

4.2.5 Gas storage volume

The gas storage volume can be measured using the flow and pressure data of the data logger and observing the withdrawal of gas from the digester.

4.2.5.1 *Raw data*

Observing the storage volume of the biodigester can be done by determining the maximum digester pressure. First the maximum digester pressure has to be determined. For some digesters, this is visible by the fact that the pressure does not cross a certain value. Figure 32 provides an that show that the digester pressure of biodigester 1 that seems to have a limited pressure of between 70 and 75 cm H2O.

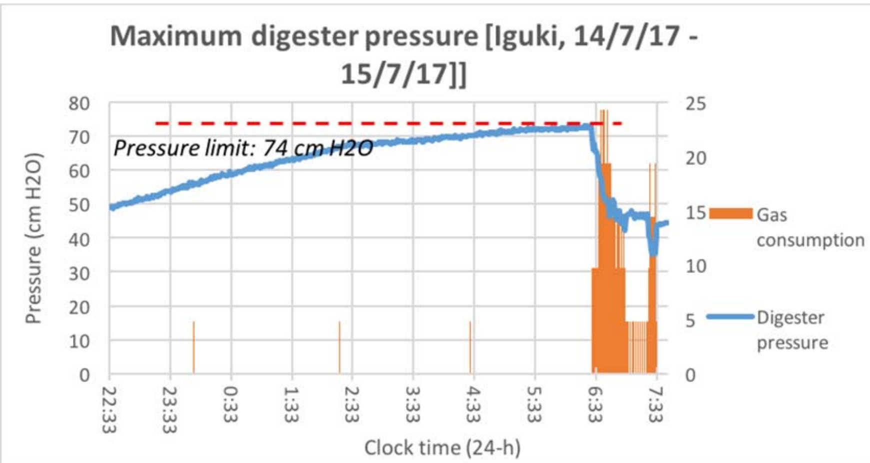

Figure 32: determination of the maximum pressure of a biodigester.

The storage volume of biodigester 5 (KENBIM, brick dome), 10 (Rehau), and 12 (Blueflame) was determined. For digester 5 an available storage volume of 1430 liter was measured, which is represented by the total volume of the cooking period that is presented by Figure 33. For an 8 m^3 digester this is around 18% of the total volume, which is a reasonable number. During that period of gas consumption gas pressure dropped from 73.8 cm H2O to 14.4 cm H2O.

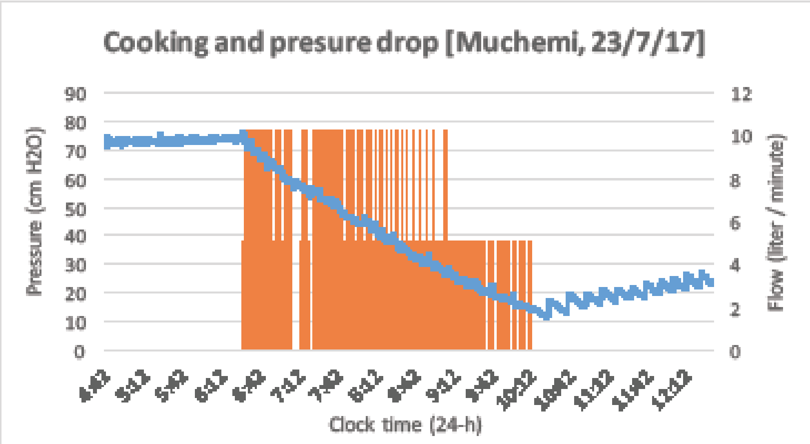

Figure 33: pressure drop after almost full withdrawal of storage volume.

For digester 10, a total gas volume of 244.9 liter was withdrawn. In this period the pressure remained constant at around 2.7 cm H2O. Note that the the data logger was an obstacle for cooking and the digester was producing gas optimally. The flow obtained from digester 12 amounted 1511 liters and the pressure dropped from 5.6 to 3.0 cm H2O.

4.2.5.2 *Accuracy of determining storage volume by data logger*

The digester pressure of biodigester 5 decreased, but there was still gas available in the dome at the moment that the household stopped cooking, since the pressure after cooking was 14.4 cm H_2O. It is hard to determine what volume is represented by.

A biodigester needs to be treated as an open system, since gas is produced internally, slurry can either be ejected of flow back to the digester and gas can be withdrawn. When gas is consomed there are three changing parameters. The number of moles of the gas are reduced, leading to a decrease in volume. Because of a drop in the digestate level, the pressure on the system gets reduced. When the exact measures of the biodigester are known, this process could theoretically be monitored. For brick-dome digesters this seems to be an unreliable method since all digesters are handmade and the dimensions are likely to vary. For bag and floating drum digesters this is not possible.

Another factor that needs to be taken into account using this method is the fact that withdrawing gas from a full digester may take up to a number of hours. To determine the storage volume the estimated volume of gas that is produced within that time frame should be subtracted from the recorded volume.

Volume stored = Volume measured (0 – t) - Volume produced (0 – t)

4.2.5.3 *Added value of visual observation of gas consumption*

For non-solid-state biodigester types visual observation can add value to the estimation of the actual storage volume. During the measurements from digester 12 (Blueflame) it became clear that the position of the drum in comparison to the part of the digester containing the slurry shows what percentage of the storage is used. This is the case when the drum is totally up (full) and the edge at the downside of the drum is visible. The total gas storage volume is used when the upper side of the drum is almost at the same level as the slurry volume. Visual observation is a good addition to make the results retrieved from the data logger more thorough.

For bag digesters, another issue occurs. For digesters like the Rehau type the pressure for cooking is often not produced by the digester but artificially produced by a load on the gas storage bag with closed valve. It was observed that the load is repositioned or new load is added when the pressure drops. The user basically adapts the pressure to its demand. Also, with open valve it is still difficult to detect the maximum pressure of a bag digester, since the pressure sensor does not seem to be developed for low pressures, as described in section 4.3.3.2. Also for bag digesters determining the load of the bag is easier and more accurate by visual observation than by data logger.

However, for both methods the flow meter of the data logger is still required for determining the total volume that was withdrawn from the digester.

4.2.5.4 *Total volume over total pressure drop as measure for storage volume*

Determining the storage volume by analyzing the total flow during a maximal pressure drop seems to be adequate for a brick dome digester. However, for bag or dome digesters determining the maximum pressure is arbitrary.

4.2.5.5 *Key findings*

The only reliable method to find the actual storage volume is analysing the flow during the maximum pressure drop and measure the flow and subtract the estimated gas produced in that time. Doing this by using household data will give a quite accurate number, but is probably not complete enough to contain a pressure drop from maximum pressure to a near-zero pressure. Also, for low-pressure digesters it is hard to find the maximum pressure.

Storage volume data	Accuracy	Completeness
Data logger (household)	4	3

Table 24: data quality ratings for actual gas storage volume.

The most obvious and reliable option appears to determine the total gas storage volume on an experimental basis. When a biodigester is used for research purposes the maximum pressure can be determined easily and the total volume can be withdrawn in one go until the minimum pressure that is required for satisfying cooking is reached. In a household setting this seems to be difficult though.

4.2.6 Investment costs

For determining the financial performance of the biodigesters the survey and the database were used.

4.2.6.1 *Data quality*

The database was used in order to determine the cost profile. For all of the biodigesters no cost profile could be found Price indications were retrieved for all of the surveys . Most showed a price range of 85,000 – 100,000 KES. Most indications were given with a precision of 5,000 KES, which is equal to around $50. Most owners seemed quite secure about their price indication, also for the plants that were built a number of years ago. One indication was given with a precision of 500 KES ($5). Some digesters are made out of cheaper second hand materials. It is debatable whether this make the price indication less representative to the average costs of the digester type.

The missing cost data from the database indicate that the database is not very complete. Since the BCE is responsible for sending the cost profiles to the KBP administration, it depends on the corresponding BCE whether the information of a plant is missing. All the plants of the fieldwork did not have price indications. The plants from Rehau and Blueflame were not registered in the database because they are part of the showroom and not for domestic purposes. According to KBP the cost indications have a high accuracy.

Owner	Price Indication Survey (KES)	Additional costs survey (KES)
1. Igoki	90,000	-
3. Iguchia	100,000	Piping (8,000)
4. Mbaya	100,000	Slurry pits, stove, piping (31,000)
5. Muchemi	100,000	-
6. Kiambi	85,000	-
8. Mari	95,000	Slurry pits, stove (9,500)
9. Kibui	62,500	-

Table 25 overview of purchase price indications from surveys. Performing the survey with household 2 and 7 was not possible. The sites of owner 10, 11 and 12 were test sites and the survey was not completed.

First of all, it could be due to the fact that it is another digester type than most of the other measured biodigesters, which consist of mostly brick-dome types. However, in this case the digester was partly made of the second-hand. This was the case for digester 9, which has remarably low costs. This leads to the question how to deal with digesters that are made out of second hand material. A reasonable approach is to only include the cost profiles of biodigesters that all competely or largely made of new materials.

Another probable reason why the costs of this digester was so low is that the volume of the digester is that the volume is just four cubic meter. Less material is required and the installation effort is lower. To analyse the costs in a comparative way it is therefore important that the costs of different digesters are only compared with digesters from the same volume class.

4.2.6.2 *Key findings*

The data quality scores for investment costs are presented in Table 26. The cost profile is rather easy to determine. The KBP database provides accurate data but is quite incomplete. User surveys show that all biodigester owners know how much they paid for the digester and can even specify accurately what digester compartments were or were not included in the price. Note that updating the database could increase the completeness.

Investment costs	Accuracy	Completeness
KBP database	4	2
User survey	5	5

Table 26: data quality ratings for investment costs.

4.2.7 Ease of use

The ease of use was determined using survey data and visual observation.

4.2.7.1 *Raw data*

In the survey, it was asked to what extent the biodigester also have negative aspects. The survey has led to the issues presented in Table 27.

Digester	1.	2.	3.	4.	5.	6.	7.	8.	9.	10/11.	12.
Score	1	n/a	1	1	1	2	n/a	1	2	- [a]	- [a]
[a] These values not available because the corresponding biodigester where installed on test-sites and the users are employees of the BCE and thus are not expected to answer the question in a objective way.											

Table 27: presentation of the answers to the survey question that deals with the negative aspects of biodigesters.

It is notable that only rather positive answers are provided. That might be representative, since there are only results for the brick dome type digesters. As explained in appendix 8.4.1.2, these types of formulation of questions was not effective, especially because it seems to be difficult to get negative feedback from households on biogas in general. Therefore, the results do probably not provide aspects that represent a complicity in a satisfactory way. It is recommended to avoid using these concepts and to ask an open survey question in which the respondents are asked to mention only negative aspects:

Name 3 negative aspects that come along with the use of your biodigester

Another contribution that can improve the quality of the answers is person that asks the questions or provides the survey. When a staff member of Kenya Biogas Program or the mason takes part in the discussion, owners tend to be socially correct and answer rather positively.

Estimating ease of use by visual observation demonstrates a number of obvious advantages and disadvantages of the data logger. An example is the fact that for the Rehau digesters balast needs to be placed on the bag for proper cooking. Blueflame is less easy to fill because of its high input. However, not all pros and cons in this field are clearly visible and getting the complete overview requires the input from the persons that feed the digester and use the biogas on daily basis.

4.2.7.2 *Measures for ease of use*

As explained, using a scale as survey variable appeared not to be successful. A better quantitative alternative that can lead to comparative results in parallel studies has not been found. With the current experiences it appears to have more potential by leaving the question open. To value the digester types based on the open answers provided by the survey or visual observation.

4.2.7.3 *Key findings*

Performing visual observation can create a good impression what the user issues look like, but a single observation has a high probability to overlook certain aspects. A user survey with improved and open questions could be less average, but the respondents can address a complete lists of performance aspects related to ease of use.

Ease of use	Accuracy	Completeness
User survey	3	5
Visual observation	4	2

Table 28: data quality ratings for ease of use.

A robust measure for the performance in the field of ease of use has not been found yet. The question is whether the ease of use of one digester compared with all of its pros and cons be compared with other types. This question has not yet been answered.

4.2.8 Robustness

The robustness was estimated by user surveys and visual observation.

4.2.8.1 *Data quality*

Most households found it hard to estimate the amount of wear and tear to their digester, in order to provde an answer on the question in the survey that focusses on robustness. First, they found it hard to criticize the digester quality. Secondly, they did not know what to focus on and usually came up with short-term problems not related to the system itself, e.g. stove problems. Eventually, data for the wear and tear of the digesters (Table 29) was all retrieved all by visual observation, by checking the visible parts of the biodigester. The maintenance history was well-known by the household, budgets inclusive.

Digester owner	Any wear or tear?	Specify	Maintenance
1. Igoki	No	-	-
2. Mutwiri	No	-	n/a
3. Iguchia	Slightly	Wear in concrete of expansion chamber	-
4. Mbaya	No	-	3x Removing water from pipes (3000 KES total)
5. Muchemi	No	-	-
6. Kiambi	No	-	-
7. Unknown	No	-	-
8. Mari	Slightly	Wear in outside wall of expansion chamber	-
9. Kibui	Substantially	Cracked plastic cover and inlet tub	-
10. Rehau cov.	No	-	-
11. Rehau unc.	Slightly	Traces of leakage	-
12. Blueflame	No	-	-

Table 29: report of wear & tear and maintenance. For the cells that do not contain information, no wear and tear or maintanance was recorded.

The rate of wear & tear that was measured was low for most of the households. Only a few digesters showed limited wear and tear, in most cases insignificant issues. Some biodigester had a damaged input vessel, which was made out of second hand components of old digesters. Digester 11 showed traces of leakage in the soil.

The most important wear and tear would be in the digester itself. For none of the brick dome types any internal wear and tear could be detected, because all of the observed brick-dome digester types were types that were built in the ground and covered with soil. The visible parts of the dome where mostly undamaged. A way to know more about the internal condition of the digester could be a better pressure test to find out whether leakage occurs in the digester.

4.2.8.2 *Measures for robustness*

With the obtained data an attemt was made to determine and compare lifetimes. No robust results were generated, which shows that this method is not adequate when the scale is unspecific and the digesters are only a few years old. Determining the lifetime requires older digester and more detailed benchmarks that are not easy to find.

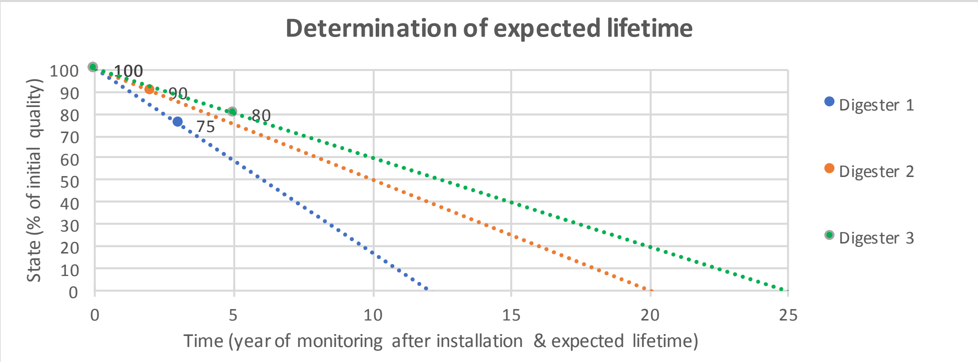

Figure 34: concept of determining the lifetime of a biodigester in a more accurate way.

It is advisable to create a more precise scale of the digester state that can be used for more accurate extrapolations, such as visualised in Figure 34. This requires benchmarks to determine the extent of wear and tear, and the effect on the lifetime. How to develop a determination method that can be used for multiple digeter types and including maintenance remains an unclear.

4.2.8.3 *Key findings*

Determining the robustness of a biodigester seems to be a performance indicator that is not easy to determine in an accurate way, which becomes clear in Table 30. Households are not likely to indicate whether the digester experiences wear & tear. Performing by visual observation is slightly more accurate. Since most parts are not visible and internal damage cannot be detected with the proposed method the method is very uncomplete.

Robustness	Accuracy	Completeness
Survey	1	1
Visual observation	2	1

Table 30: data quality scores for robustness.

4.2.9 Surface requirements

The required surface was measured by visual observation and using the survey. Although some households tried to make accurate estimations of the surface, the numbers did not seem to make sense. Therefore, all observations have eventually be done by visual observation. Data on the surface were obtained from ten of the total of twelve digesters. The surfaces of the digesters vary from 3.8 to 16.8 square meters. .

Although measuring the surface by visual observation gave reliable results, the method of estimating is arbitrary, since the surface is mostly not rectangular and the surface of different components are often not connected. A number of approaches were used (appendix 8.4.5)to determine the surface. Eventually, with the experiences from the research it can be advised to select second method that is described in the appendix. The third method is advised in the following cases:

- The soil between the input tub and biodigester is occupied for other purposes than the biodigester (which was the case for the installation of digester 5).
- The input tub is far away (more than 3 meters) from the digester (digester 8).

The fourth method can be used when the dimension of the input tub and the output or expansion chamber are negligible (less than 30 cm diameter), which was the case for digester 10, 11 and 12.

4.2.9.1 *Measures for surface requirements*

Comparing the specific surfaces shows that the values (Figure 35) are near to each other and vary from 0.9 to 2.0 m^2/m^3. It indicates that of the measured digesters the Blueflame occupies a low surface (1,2 m^2/m^3) and the Rehau type a rather large surface (m^2/m^3). The Kenbim and Simgas type score in between, with the Simgas type slightly better than the Kenbim, which is likely because the expansion chamber of the Simgas type is built on top of the digester volume, therewith saving space. Note that these results are no decisive numbers on the surface performance of these digesters.

It seems that the unit is a suitable way of expressing the surface requirements, because it matches with the expected outcomes.

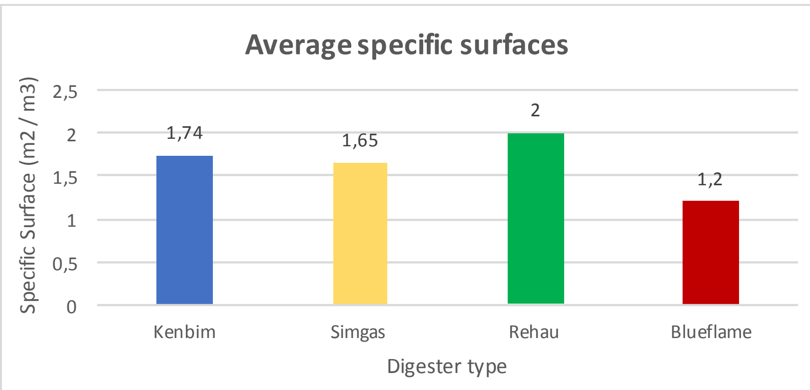

Figure 35: volume specific surface of four different digester types

4.2.9.2 *Key findings*

An overview of data quality scores is presented by Table 31. Although some respondents might try to guess properly, user surveys does not seem to be an accurate way of analysing the surface of a biodigester system. When the correct method of estimating is used a quite accurate estimation can be made by visual observation, although the methods remain slightly arbitrary and the volume-specific surfaces of different digesters seem to be quite comparable.

Surface	Accuracy	Completeness
Survey	1	3
Visual observation	3	5

Table 31: data quality scores for surface requirement.

4.3 Alternative options for measuring tools

A number of improvements can be done on the process or data quality of the existing measuring tools, of which improvements to the data logger are the most relevant.

4.3.1 Improving KBP database and survey approach

The KBP database could be kept up-to-date to get a reliable investment price indications as complete and accurate as possbile. This requires more time .

An alternative in Kenya for the initial approach of the survey is to perform the surveys via by phone, e.g. by using the services of the *Technobrain* call center. This would implicate that the costs and required time would decrease, since the logistics are cut away. The survey is not specifically complicated compared to current interviews to biodigester owners that are currently held, so the data quality is not assumed to decline.

4.3.2 Alternative data logger options

The data quality of the data logger is not optimal and using the device has many disadvantages. Upgrading the existing data logger or developing an improved data logger (data logger 2.0) are options.

4.3.2.1 *Refurbished ABPP data logger*

Field observations showed that the current data logger is not well-calibrated, with variations in flow records of 15% and in pressure records of 10%. Recalibration of the data logger is an option. The shipping costs for sending data loggers back to the Netherlands are high [37]., due to the size of the device. The question is whether it is worthy to invest in the data loggers, since their estimated lifetime has already exceeded. It is expected that the flow meter is already affected by the H_2S from the biogas [37].. A budget option for the flow data is to test all flow meters and pressure sensors, determine the difference in calibration and calibrate digitally after importing the data in excel.

The current data logger appears outdated and because of its size it is unsuitable for frequent long-distance shipping, which is likely to be required to perform studies in different ABPP countries.

4.3.2.2 *Data logger 2.0 by Pronon*

A new version of the data logger can be designed to overcome most of the described problems. In conversation with the developer of the ABPP data logger the options for the development of a new data logger was discussed. The following preferences are desired:

- At least the same robustness and accuracy of the current data logger
- Accurate and well-calibrated flow meter with a longer lifetime
- Minimized size and weight of all data logger components, for easier transport
- Longer temperature sensor cables
- Easier data collection
- Data records for every 5 or 10 minutes, instead of every minute

The most vulnerable parts of the data logger include the flow meter and the batteries, the other parts are expected to be relatively robust [37].. With the current technology it would be better to use digital flow meters, which are much smaller, likely to be more accurate and nowadays cheaper [37]. They are barely vulnerable to corrosion . Hence, they do not require a desulfurizer, The same or better chips for pressure and temperature sensors can be used [37].. Longer temperature sensor cables can be used, but wireless options in the same price range can be used. Nowadays it is easy to transfer data by GPRS-connection [37].. It requires a SIM-card and some contract costs for using phone connection services, which are probably lower than the costs for visiting the plants. The records of the data takes place every 10 seconds with the current device, but is programmed to record for every minute. This could be adapted to any preferred interval [37].

4.3.2.3 *Simgas data logger*

Some BCEs have initiated performance measuring studies, since it provides them a number of specific business benefits (appendix 8.5.2). For Simgas this has led to the development of a data logger that monitors the following parameters [47,48]:

- Barometric pressure (mbar);
- Internal pressure (mbar);
- Ambient air temperature (°C);
- Battery voltage (V).

A data point containing these parameters is written every five minutes and sent via GPRS-connection to a digital platform, provided by Steamco [47,48]. The records can be downloaded by.csv file via Steamco.

Simgas has some data loggers containing budget digital flow meters [47]. During the field study in Karatina (biodigester 8, 9) the records of the Simgas flow meter were installed in series with the ABPP data logger for comparing the flow and pressure data. The records from a number of cooking sessions from biodigester 8 were analysed. An comparison was made between the ABPP flow records and the uncalibrated Simgas records. Figure 36 shows us that there is a very high regression between the records of the ABPP data logger and Simgas data logger, which indicates that these two data loggers are able to be used parallel comparatively. One side note is that the Simgas data logger is unable to detect small flows (e.g. flow records from milkchiller).

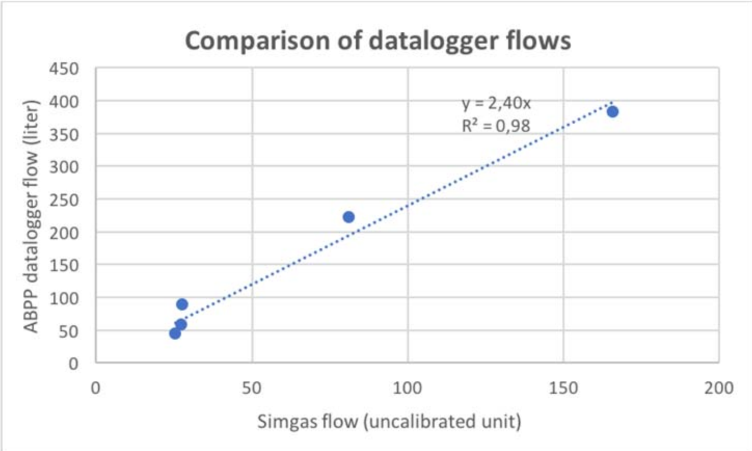

Figure 36: comparison of flow measured by Simgas (uncalibrated) and ABPP flow meter show very strong regression for a number of cooking periods for biodigester 8.

Observations of the comparison of the two types of data loggers of biodigester 9 present different results. The gas flows of every day of the measuring study were summed up and analyzed, showing an R^2 of only 0.008. This lack of regressions means that the daily records of the two data loggers do not show many comparable trends, which also becomes clear in Figure 37. Although some similar some trends are observed in the data it is especially notable that many trends in the Simgas flow data do not show any similarity with the ABPP data.

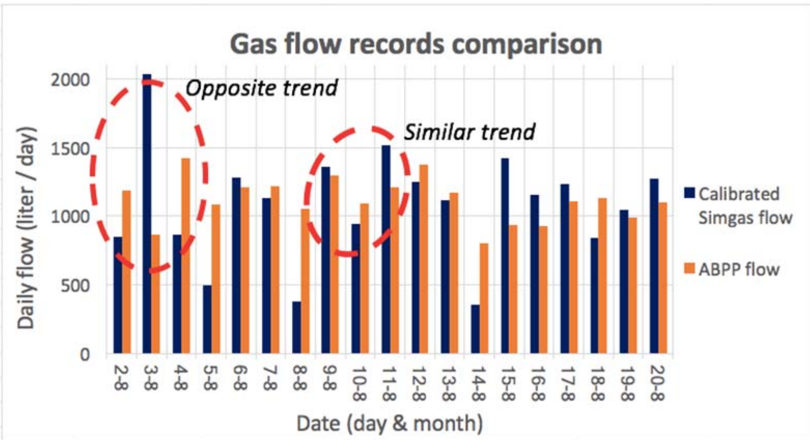

Figure 37: comparison of flow of household 9 measured by Simgas (calibrated) and ABPP flow meter show very low similarity.

It seems that the flow meter that is currently present in the Simgas data could be very accurate for one flow meter, but is unreliable. This makes the flow data of the budget meters only indicative. This matches with the motive of Simgas, since they aimed on only detecting flows and not in particular on determining the absolute values volumes. More reliable and costly flow meters are available and could be installed. It is estimated to have equal costs to the indication of the flow meter costs by Pronon.

4.3.2.4 *Data logger without flow meter*

A detailed analysis of pressure data could substitute the expensive flow meter. A decrease in pressure represents gas withdrawal and an increase represents production. Also feeding could be estimated by analysing steep pressure increases (Figure 38), making the logbook unnecessary. Observations show that by analysing the pressure dynamics it is indeed possible to distinguish these events. The slopes of the pressure changes ($\delta p/\delta t$) due to cooking, production and feeding were observed. Feeding ($\delta p/\delta t > 20$ cm H_2O /h) and cooking events ($\delta p/\delta t$ = -20 to -50 cm H_2O /h) are obviously much steeper than the pressure increase due to gas production ($\delta p/\delta t$ 1.5 – 7 cm H_2O/h).

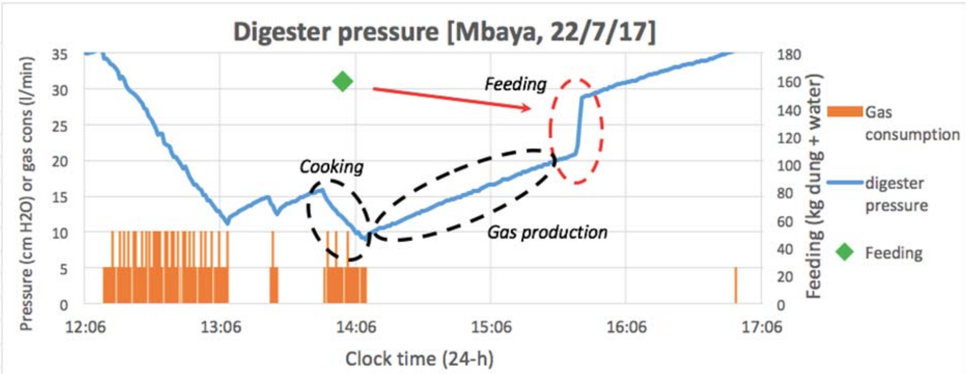

Figure 38: visualization of the increase of digester pressure due to feeding and cooking.

The pressure dynamics that correspond with cooking, production and feeding are presented by Table 32. Digester 2 showed a pressure increase of around 7-9 cm H_2O for around 150 kg feedstock, while biodigester 6 showed 2-4 cm H_2O for 85 kg. Hence, relating pressure increase to feedstock is indicative but not very accurate. Furthermore, feeding is hard to detect when it occurs during cooking. User behaviour also plays a role: when the digester is fed before on maximum pressure before cooking slurry ejects and the pressure does not increase significantly. Feeding therefore can only be detected when there is no slurry ejection during feeding. For floating drums digesters the rate cannot be detected and for bag types it is very unreliable due to the low pressures.

Pressure increase or drop in cm H_2O	Cooking (1 hour)	Gas production (1 hour)	Feeding (1 hour)	Feeding (1 time)
Solid-state (Kenbim, Simgas)	-25 to -50	1.5 to 7	> 20	2 to 9
Bag type (Rehau)	-0.5 to -8	< 1	> 10	1.5 to 3
Floating drum (Blueflame)	0 to -4	< 0.1	Not detected	Not detected

Table 32: pressure dynamics due to cooking, gas production and feeding that have been determined by observation of the pressure data obtained by the ABPP data logger.

There are large differences in absolute pressure increase rate during gas production or consumption. To determine the produced or consumed volume of gas, the effect of other factors should probably be taken into account, such as the volume and shape of the digester. For bag and floating drum types relating to pressure dynamics is generally problematic, so the translation seems to be optional only for solid-state digesters. To make a reliable translation it requires a much more in-depth analysis of the relation between these three factors and the digester dimensions. For analysing datasheets of a longer period, it is unavoidable to analyse the events automatically by algorithms. However, it remains questionable whether this translation will lead to any reliable figures [47], data loggers with flow meters are recommended.

4.3.2.5 *Comparison*

It is important to determine whether it is advisable to invest in a new data logger. The process assessment of Table 33 was made for a new data logger, excluding the investment costs. This includes all discussed new devices, since they operate similarly and have approximately the same size so the same logistic requirements. The data logger is slightly easier to use, because there are less aspects that risk the operation of the tool and it is likely that the time records of the produced data is already calibrated. The only household visit that is required is the installation and uninstallation, therefore scoring better on intervention, affordability and time requirements.

	Simple	Intervention	Affordability	Time
ABPP data logger	1	1	1	1
Data logger 2.0	2	2	2	2

Table 33: process scores of new version of data logger in comparison to process scores of conventional data logger

The data that is generated by a new data logger depends on the properties that are applied. A data logger with a budget flow meter can be accurate, although this statement is not valid for all considered units. The robust flow meter is assumed to be very accurate and complete, although this has not been proven yet. The potential of determining the flow by pressure data has not become clear but is expected to be less accurate and some feeding or cooking events might be overseen.

Dung input	Accuracy	Completeness
Data logger	4	4
DL 2.0 + budget fm	3	2
DL 2.0 + robust fm	5	5
DL 2.0 without fm	3	4

Table 34: : data quality scores for three proposals of a new data logger in comparison to data quality of conventional data logger

The process score for the second version data logger seems to be better for the new generation data logger, and the data quality is expected to be better. The investment costs are important to consider, which are estimated between $893 and $1080 per data logger (appendix 8.5.3.1) inclusive shipping costs, which is estimated on roughly half of the costs. Since the costs of use (based on six households) are estimated on $1180 for the existing data logger and $650 for the new data logger (inclusive international shipping, based on one study of 6 digesters) it shows that use of the new generation data loggers will be profitable when more than two measuring studies are performed, which is likely to occur.

4.3.3 Importance of performance indicators

The survey that was performed among several biodigester experts in the network of KBP parallel to the technical fieldwork provides the results of Figure 39. The following observations are specifically important to point out:

- Robustess and gas pressure are mentioned as the most important performance indicators, followed by ease of use, specific gas production and stability of gas production.
- Required surface is considered as the least important indicator followed by gas storage volume and investment costs.
- Remarkable is that the ABPP respondents described the specific gas production as the most important performance indicator, while it is one but last in the ranking of the non-ABPP respondents.

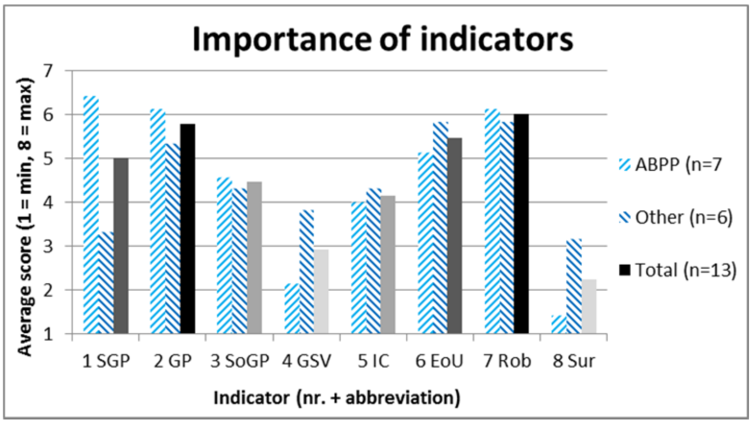

Figure 39: scores of importance of performance indicator according to biogas expert survey. The group of ABPP (including KBP, SNV, Hivos) respondents, non-ABPP respondents and the total group of respondents are represented.

5 Discussion

5.1 Selection of measuring tools

The scores of the process analysis will be discussed first (section 5.1.1), followed by single scores of the data quality per performance indicator (section 5.1.2)

5.1.1 Process analysis

The scores for the four different aspects (*simplicity of use*, *intervention of households*, *affordability*, and *time requirements*) that determine the process quality are viewed in table 29. The overview (Table 35) leads to the following overall observations on the process quality of the measuring tools:

- The KBP database has excellent scores in all fields, while the data logger has the lowest rating for all fields. The data logger is an unattractive measuring tool in every process aspect.
- Except for the data logger all measuring tools have sufficient scores on simplicity. Intervention is a more problematic aspect for all tools except for the database.
- The scores on affordability and time show more variation between the tools. After the database the user survey has the best scores, followed by visual observation, logbook and the data logger.

By applying the weighting factors on the scores for the process phase a total weighted score is calculated. As expected the database has the full score and the data logger the minimum score. In between the survey scores the best, followed by the observation and logbook, which have comparable scores. This assessment is not decisive for the selection of measuring tools, but can help in the decision the selection process.

	Simplicity	Intervention	Affordability	Time	**Weight. total**
Weighting	50%	10%	20%	20%	**100%**
Database	5	5	5	5	**5**
Survey	4	3	3	3	**3.5**
Logbook	4	1	2	2	**2.9**
Data logger	1	1	1	1	**1**
Observation	4	1	3	2	**3.1**

Table 35: overview of scores for aspects of different measuring tools, including weighted scores

5.1.2 Data quality analysis

There are nineteen ratings given for the data quality for five measuring tools that measure the performance indicators.The scores on data quality lead to the following overall observations:

- In none of the cases a perfect score of 5 exists. However, there are many scores of 4 and 4.5, which represent good data quality.
- Taking into account the five measuring tools, all parameters except for robustness can be explained properly.

- The data logger proves to be an unmissable measuring tool for good data for the technical performance indicators.
- For operational indicators data can be obtained either by a combination of database + visual observation or by Survey. The second combination provides the best data.
- To obtain data on dung input, for calculating the specific gas production, the logbook provides good data quality and one moderate data can be obtained by visual observation.

Data quality single scores	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GP								
Database						2.5				5
Survey		1	3			4	4	1	2	3.5
Logbook	4.5	2.5								2.9
Data logger		4.5	4	4	4					1
Observation	3.5	1	2				3	1.5	4.5	3.1

Table 36: scores for the data quality of every performance indicator by measuring too. The next abbreviations are used: Specific Gas Production (SGP), Dung Input (DI), Gas Pressure (GP), Gas Production Stability (GPS), Gas Storage Volume (GSV), Investment costs (IC), Ease of Use (EoA), Robustness (Rb), Required Surface (RS).

In order to find a measuring method with good data quality on most indicators and that includes less tools with low process scores, a number of scenarios are possible.

When looking only at data quality, the scenario of Table 37 can be suggested. For every indicator the measuring tools that provides the best quality data is selected. This includes using the logbook for measuring dung input, data logger for technical indicators, visual observation for robustness and surface and the survey for investment costs and ease of use. The average data quality would score 3.9 out of 5. It is however desired to select a measuring method that includes as less measuring tools as possible and excludes the tools with bad process scores. The bests-scores scenario requires in total four methods, of which two have process scores lower than 3.

Scenario 1: Best records	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GP								
Database										5
Survey						4	4			3.5
Logbook	4.5									2.9
Data logger		4.5	4	4	4					1
Observation								1.5	4.5	3.1

Table 37: overview of the data quality and process scores for the best records method

A second scenario that excludes the survey and logbook from the measuring method, but is able to obtain data for all indicators is possible. In this *visual observation scenario* (Table A 1 of appendix 8.5.1) the database is used for determining the investment costs and visual observation is used for all other indicators that are not covered by the data logger, including dung input. Although the average data score would be lower (3.5) there is only one measuring tool that scores lower than 3. Hence, the survey-based scenario is easier to use, but provides data with lower quality.

A third scenario is excluding visual observation and the database, whereas including the logbook and survey (Table A 2 of appendix 8.5.1). The average data quality is 3.6 and it includes two measuring with process scores lower than 3. Hence, the scenario based on observation scores lower on data quality, but has less tools with moderate or bad process scores involved in comparison to the second scenario.

The differences between these scenarios are however marginal and a number of other aspects have not been considered yet. First of all, for all methods so far it was assumed that the dung input is determined by the household since the feeding varies per day. In case it is possible to find households willing to standardize their dung strictly to an amount advised by ABPP, it would mean that dung input does not require a measuring tool at all (Table A 18 in appendix 8.5.1). Only the data logger and a survey would be sufficient to obtain data for all performance indicators, including specific gas production. The data quality would be 3.4 and only one measuring tool scores lower than 3.

The differences of the process scores between the scenarios are marginal. In comparison to the inconveniences that come along with using the data logger the process scores of the other tools are relatively unimportant in a measuring study that also includes the data logger. Any alternative scenarios in which the data logger can be excluded would be beneficial. From the technical parameters the gas pressure could be measured by survey and the gas production by logbook. The average data quality would be 3.0 and only one tool scores lower than 3 for the process phase. This method, however, does not cover two indicators: stability and storage volume.

5.1.3 Analysis of alternative measuring tools

Comparison of the four scenarios how that the data quality gains are substantial when a measuring method is selected that includes tools with slightly lower process scores. The problem of the proposed method is that the process is still complicated, expensive and labor intensive. Hence, setting up performance measuring studies in different ABPP countries coordinated by biogas technicians without significant performance measuring experience is expected to be problematic and costly. It is likely that performance studies will lack scientific robustness or reliability, which was the case in previous experiences.

Developing a second generation datalogger leads to better process scores of the data logger, making the logbook less relevant as measuring tool, which means that dung input can be standarized. Thereby, the measuring method is more likely be usable for local biogas experts with limited expertise in performance measuring. Furthermore, a second generation data loggers is likely to produce high-quality data and the operational costs will be much lower, especially when shipping of the dataloggers between ABPP countries is necessary. It is recommended to make the investment when the ambition of performance measuring study remains unchanged.

5.1.4 Including importance of measuring tools

For some performance indicators it is more crucial to generate quality data than for others, since not all performance indicators have the same importance to the biodigester performance. An important question is what the importance is of the individual indicator. For the interpretation of the results of 5.1.1 and 5.1.2 the findings from biogas expert surveys have a number of implications:

- The importance of robustness (#1 important) makes clear that a better method for determining the scores for this indicator needs to be developed.
- The importance of ease (#3) indicates that it would be better to use the survey as measuring tool and this could be an advantage to the third scenario. Also investment costs (#5) would benefit from that strategy.
- The survey scenario would only be a disadvantage for surface (#8), the least important indicator.
- For gas pressure (#2) the data logger is important. For specific gas production (#4 and #1 for ABPP respondents) and stability (#5) the data logger is crucial.

5.1.5 Other remarks on scores

Process scores were given to measuring tools as a whole. This is consindered being representative for the data logger, survey and logbook. For instance: a survey with questions on 5 performance indicators does not have any additional efforts (in terms of time, finance, complexity and intervention) in comparison to questions on 2 performance indicators. For visual observation, however, this is more nuanced. Determining the digester surface and robustness can be performed in a matter of minutes without much intervention, while the other indicators require a number of hours and intervention and depend strongly on the plans of the households relative to the visits of the researcher. Hence, visual observation can be a useful tool for surface and robustness, but it is advised to be only used occasionally for the other indicators when possible.

Furthermore, the comparison of the previous section does not describe co-benefits of measuring tools. Although the logbook is a measuring tool with limited data quality on gas consumption, it benefits the ease of using the data logger, since the cooking records are useful for calibrating the time of the data logger and can prevent mistakes during the data analysis.

When different measuring tools are combined it is probable that the total costs and time requirements are the sum of all tools. When performance measuring is planned well it can save time and costs due to efficiency in logistics. Hence, it is more important to focus on avoiding the measuring tools with the worst process scores (data logger), than to focus on marginal differences between the scores of others (survey, logbook, visual observation), proving that the best scores scenario is advisable.

5.2 Limitations

The data quality and process assessment led to a clear overview of the potential of the considered measuring tools. However, assumptions were made and the scope is limited. Scores that were given to process and data quality are based on a limited number of observation. Reliability can be affected due differences in the estimation of scores and weighting factors.

5.2.1 Process & data quality scores

The values given for the process and data quality scores can be affected in different areas. Uncertainty of the results is created by a number of factors.

First of all, most of the observations were done in relatively developed areas, with mainly literate biodigester owners. In areas where the illiteracy rates are higher it is likely that the logbook performs worse and, hence, should be avoided. Secondly, a number of sufficient well-working biodigesters was available. In other areas it can take a longer time to find biodigesters suitable for the research. Furthermore, only households in Kenya were tested. The willingness of the households to cooperate could be different in cultures of other ABPP countries.

Furthermore, the cost indications that were made for the process scores were based on a number of assumptions. Especially the investment costs of new data loggers are rough numbers and the shipping costs are estimations.

5.2.2 Weighting factors

The weighting factors for the process phase are based on a research-specific decision. For specific research projects adjusted weighting factors are appropriate, depending on the aim of the research, the selected region, or the size of the study. Changing the values of the weighting factor are advisable in two cases.

First, it is possible that the culture of the households includes a more preserved attitude towards cooperation with performance measuring studies and intervention is a much more important factor (50% of weighting). As shown in Table A 13 in appendix 8.5.1, this would affect the process scores of the survey (-0.2), the logbook (-0.8) and visual observation (-0.9). As expected the process cores of the database and data logger remain unchanged. Hence, the method based on survey with standardized dung input (scenario 4) gets relatively attractive for studies where household intervention is relatively important.

Second, in case a large-scale performance measuring study is developed for condition-specific performance measuring the costs and time requirements could become more important as the scale increases. ABPP could choose to coordinate the measuring studies centrally by core ABPP staff, which could make simplicity less important and increasing the importance of affordability strongly. Also time would be more important. Calculations of the new process score (Table A 12) indicates that the scores of the survey (-0.4), logbook (-0.8) and visual observation (-0.5) decline. This means that the logbook gets relatively unattractive, in case of thight budget and time constraints.

The process scores of logbook are the most sensitive to the two described scenarios, in which standardization of dung input would be recommended. Furthermore, the survey is relatively insensitive to the described cases. These observations confirm the selection of the survey for ease of use and investment costs and show that standardizing dung input is desired.

5.3 Implications:

5.3.1 Setting up a performance measuring study

This performance measuring study has shown that a performance profile can be set up that explains seven out of eight performance indicators. The best-score scenario should be adapted, which measures performance by using surveys, a logbook, visual observation and the existing ABPP data logger. When the data logger is recalibrated, scientifically reliable results can be produced. However, it is important that it is performed by staff with performance measuring and data logger operation experiences. This educes the risk of events that affected the quality of the results of previous performance measuring studies. For mid- and long-term the development of a new data logger is crucial.

A new ToR should be developed and the different options should be researched. A performance measuring method that includes a second generation data logger can be performed by monitoring biodigesters the whole year through, providing complete datasets of the performance during the whole year.

5.3.2 Widening of research boundaries

The scope of the reseach limits the usability of the advise. The limitations should be taken into account when performance measuring studies are set up.

First of all a limited selection of performance indicators was made (section 3.1.4), excluding economic and environmental parameters. Technical parameters that deal with slurry and gas quality were ignored. According to indications given by the biogas expert surveys the slurry quality is not expected to depend on the digester performance. However, for the biogas quality this is more likely and this could be included in a performance measuring method in the future. Furthermore, the performance of biodigesters could also be assessed from the perspective of assessing BCEs instead of digesters. Results from the biogas expert survey show that beside the product quality a number of business related aspects are very determining (appendix 8.5.4), such as after-sale-service. The performance definition could be widened to capture aspects that are not directly related to the biodigester itself.

The selection of measuring tools was also limited. First of all, lab analysis of the feedstock and slurry composition for estimating the gas production has not been validated as measuring tool by this research and could be used in the future. Experiences in the performance measuring studies in Rwanda show that this tool requires a long time of measuring, which is not likely to make the process of using the tool attractive. Another remark is that other measuring tools might be available that have not been considered by this study.

A last item that has not been completed in this research is the development of suitable performance measures that can explain the performance of every indicator compratively for different digester types. It is advisable to develop these measures further in case a more detailed study on the development of a measuring method is planned. In general it is likely that the development of an all-including robust measuring method requires multiple iterations. This report can therefore be considered as a first step towards a research method that eventually suits the performance measuring goals of ABPP.

Note that developing a measuring method is a matter of iterations. New experiences with performance measuring can lead to new preferences regarding the performance profile and indicators. Also, new insights in the usability of certain measuring tools can be determining.

6 Conclusion & recommendations

6.1 Conclusion

The research question was set in the following way:

How can a comparative method be developed that is suitable for mapping the performances of domestic biodigesters in Sub-Saharan Africa?

Performance is defined as the maximum biogas production per unit of feedstock (output) with a minimum of disadvantages to the households (input), taking into account technical, operational and financial aspects. A list of eight indicators covers the performance profile: *specific gas production*, *gas pressure*, *stability of gas production*, *actual storage volume*, *investment costs*, *ease of use*, *robustness* and *required surface*. During four fieldwork sessions five different measuring tools were used: KBP database of biodigesters, user survey, logbook, data logger and visual observation. Every tool was rated by a process score (includes: simplicity, intervention of households, costs and time requirements) and data quality score (accuracy and completeness).

The logbook scores moderately, the survey and visual observation score slightly better. The database does not have disadvantages, but is only useful for data on *investment costs*. The survey and visual observation are useful for obtaining data of operational parameters, whereby the survey shows slight advantages. It is advised to use visual observation only for measuring the *surface*, or occasionally when it can add value for measuring other indicators. Although the data logger has negative process scores the tool is indispensable for quality data of most of the technical parameters and there is no considerable method feasible without this tool. The logbook is useful provides accurate results on the dung input.

The selection of tools that generate the best data quality scores per indicators, described as the best-scores-scenario, is the most promising measuring method. Good-quality data can be generated for al performance indicators, except for robustness.

6.2 Recommendations

The current data logger can be used for qualitative studies in the short term, but an alternative data logger that has better scores for user aspects and data qualty is essential for reliable and scientifically robust performance studies. A new data logger is expected to be more compact (hence easier transportation), is able to send data by GPRS connections and the production and shipping costs are much lower. New digital flow meters types have at least the same quality as the mechanical ones and probably last mast longer. There are at least two alternative options for improved data loggers. When a reliable second version data logger is developed it is advised to standardize the dung input to replace the logbook.

Although a first research setup is proposed, including indicators, measuring tools and some examples of successful measures, additional research on a number of aspects is essential for a well-working research method. The following recommendations are made:

- A method for monitoring the performance in the field of the robustness should be developed, which can be used in a comparative way for different biodigester types.
- Measures are required to express the performance indicators in absolute terms. Further research should be done to develop concrete measures for all performance indicators.
- For the development of a second generation data loggers a detailed case study on the quality of digital flow meters should be done, monitoring the following aspects: accuracy of the data, robustness of the device and the minim flow (l/min) and pressure (cm H_2O) it needs to operate.
- It is advised to assess the methods that are used after any measuring study in the future to update the performance measuring protocol continuously.

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8 Appendices

8.1 Background of introduction

8.1.1 Figures on benefits of clean fuels for developing households

The most important benefits of clean fuels include:

- In the developing world, exposure to air pollution due to inefficient cooking with traditional biomass leads to 1.5 million premature deaths each year [4] as well as many negative non-lethal health effects. Cooking on clean fuels has major health benefits.
- In the case of cooking on firewood, replacement with cleaner fuels leads to time savings [4], since the time-intensive process of collecting firewood is no longer necessary, and therefore creates new educational and job opportunities for household members.
- Women are in many cultures still responsible for cooking, and the previously mentioned points especially benefits to the quality of live and changes for women.
- Charcoal or fossil fuel purchase are major expenditures for households in developing countries [4]. Stepping away from these fuels leaves financing available for other development purposes.

Replacing traditional biomass consumption by cleaner fuels also has important environmental benefits for the Sub-Sahara Africa, a region that is strongly threatened by desertification due to unsustainable land use [39]. In many areas, using firewood or charcoal for cooking purposes puts pressure on existing forests and ecosystems [4]. Clean fuels can reduce the local ecological footprint of cooking.

8.1.2 Contributions of biogas to SDGs

The impact of domestic biogas production on the development of rural areas in LDCs is considered to be promising [7,11,26]. The technology provides an affordable, independent and sustainable energy supply (SDG7: affordable and clean energy) and the bio slurry substitutes fertilizer purchases (SDG2: zero hunger) [1]. The effect of the biogas sector particularly contributes to the life standard of women (SDG5: gender equality), prevents a lot of cases of respiratory diseases (SDG3: good health and well-being) due to cleaner cooking and contributes to a lower pressure on the environment (SDG15: life on land, SDG13: climate action) [1]. In its publication on energy poverty in 2010, the International Energy Agency makes clear that ‘’energy access goals must be combined with other poverty eradication goals’’ [4]. Domestic biogas production is a multi-benefit technology that combines eradicating energy poverty with other development goals.

8.1.3 History of domestic biogas development & ABPP

Since the 1970s governmental programs have been set up to stimulate the installation of domestic biodigesters in China (27 million), India (4 million) and considerable numbers in Bangladesh and Nepal and some other Asian countries [7]. In the same time period, just some tens of thousands of digesters were installed in the Sub-Saharan Region. A significant part of the population lives in areas with fitting circumstances [9]. Estimations for this region show numbers of between 2 and 18.5 million possible installations (Table A 3). The low infiltration rate of domestic biodigesters in the Sub-Saharan Region is assumed to be the result of economic factors and a lack of local knowledge on the technology on e.g. user aspects [40].

Estimated households	*Region*	*Potential*	*Source*
2 million	Sub-Saharan Africa	Economic Potential	9
6 million	Sub-Saharan Africa	Forecast 2040	4
18.5 million	Africa	Technical Potential	41

Table A 3: overview of estimation on the potential and forecasts of biodigester installations in Africa.

In order to copy the successful experiences in Asia to Sub-Saharan Africa, cooperating development- and governmental organizations have set up programmes for building domestic biogas sectors in a number countries. In 2006 the program Biogas For Better Life was set up [9], resulting in detailed feasibility and implementation studies. In 2008 the *African Biogas Partnership Programme* (ABPP), a Public Private Partnership between *SNV Netherlands Development Organization*, *Humanistic Institute for Development Cooperation* (Hivos) and the *Directorate General for International Cooperation* (DGIS) of Dutch Ministry of Foreign Affairs [42], was set up.

ABPP supports a number of regional organizations (Table A 4) that aim to build up a feasible domestic biogas sector with and roughly 100.000 installations [10], in a number of countries with good circumstances regarding climate (warm environments and water available), urbanization (rurally populated) and economy (farmers in possession of livestock). The required financing [43] for the program (roughly €95 million) is mainly provided by the potential plant owners. External financing is provided by DGIS (32%), SNV, Hivos and African governments. SNV and Hivos do the technical assistance and educate masons and other construction workers [43], in order to create a supportive economy for biodigesters. They also research the technical performances of digesters in order know more about the appropriate digester type for specific circumstances.

The duration of the first phase of the ABPP was from 2008 to 2012. After that a second phase has started up in the period until the end of 2018 [10]. The target of total installations was set on approximately 100,000 installed digesters in the period 2014 – 2017 [44].

Country	*Organization*
Burkina Faso	National Programme of Biodigesters (PNB-BF)
Ethiopia	National Biogas Programme of Ethiopia (NBPE)
Kenya	Kenya Biogas Program (KBP)
Tanzania	Tanzania Domestic Biogas Programme (TDBP)
Uganda	Uganda Domestic Biogas Programme (UDBP)

Table A 4: overview of the national biogas programs connected to ABPP and the initial target number of installations per country in the second phase. Source: ABPP [45].

8.1.4 Valorisation of results from performance measuring method

The performance measuring method that is developed will be used by ABPP for rating the performance of conventional and new digester types, comparing them over a wide range of aspects for two main targets. The primary target is to create general performance profiles of a certain biodigester type under standardized conditions that are equal for all studies, including the temperature, feeding and the user behaviour. This can be used for the validation of product information [14]. The secondary target is to extent models of these biodigesters and develop condition-specific performance profiles [13,14] that describe in-depth how a biodigester performs under a wide range conditions, taking into account e.g. climate, water availability, type of households, etc.

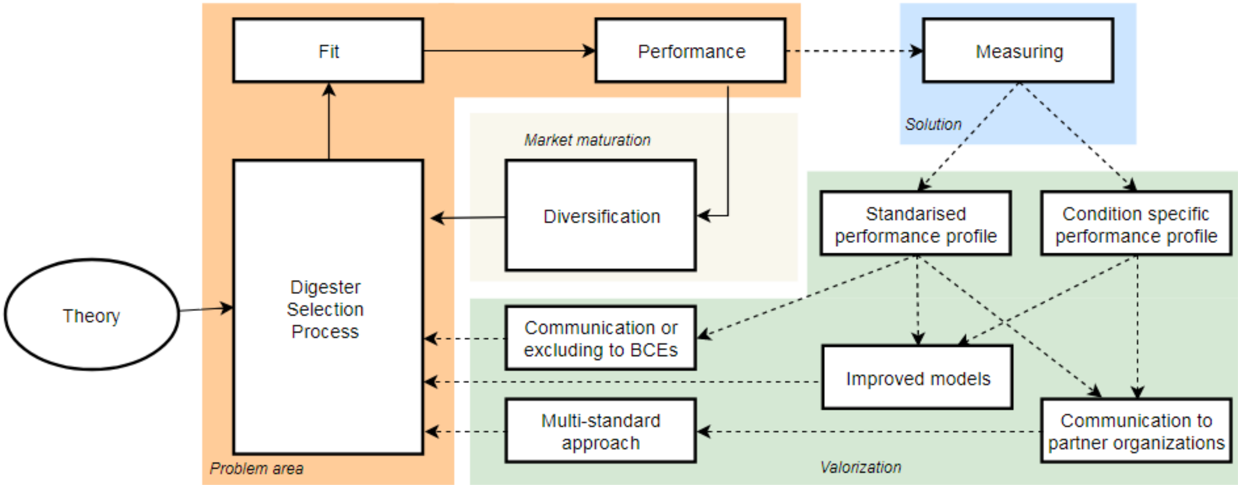

Figure A 1: visualization of the defined problem, solution (performance measuring) and valorisation.

As visualized by Figure A 1: visualization of the defined problem, solution (performance measuring) and valorisation. the performance profiles of digester can lead to a better selection process in a number of ways [13,14]:

- BCEs that provide unrepresentative product information are informed and asked to change the information or they can eventually be excluded from the national biogas program.
- The models of digester types that are used for advice on construction can be improved.
- The marketing can be changed to promote digester types have the best fit for a certain region.
- Communication to partner organizations can be adapted, to stimulate certain types that fits the region well can be done to, including the following organizations [13,14]:
  - biogas hubs of the corresponding region;
  - business associations (e.g. *saccos* in Kenya) that cooperate with the national program to develop domestic biogas through the organizations network;
  - NGOs that are promoting biogas solutions.

As result the digester selection process will be based on more thorough recommendations and more reliable product information, leading to a better fit and improving the performances and therewith the success of the technology.

8.2 Background of theory

8.2.1 Anaerobic digestion

The chemical process of biogas production is called anaerobic digestion (AD). It consists of a series of microbiological processes under anaerobic conditions [8]:

- Hydrolysis: this is the break-down of large organic molecules by water into smaller molecules. This makes the material available for bacteria.
- Acidogenesis: the smaller molecules are processes by fermentative bacteria and turned into mostly methanogenic substrates (substances that could be used by methane producing bacteria), such as acetate, hydrogen, volatile fatty acids (VFAs), alcohol and carbon dioxide (CO2).
- Acetogenesis: certain substrates that are not yet able to become processes (such as VFAs) by methanogenic bacteria are turned into acetate, hydrogen or other methanogenic substrates by certain microorganisms. This occurs parallel to methanogenesis.
- Methanogenesis: hydrogen and acetic acid are processes into methane by methanogenic bacteria. By products are carbon dioxide and water. Of the four processes methanogenesis is the most crucial step for a well-functioning digestion process, since it is the slowest of the processes and is strongly influenced by external factors, such as temperature and the pH.

The four sub-processes of AD occur automatically under anaerobic circumstances without addition of bacteria colonies. When the circumstances are more optimal, the gas production (and usually also the production efficiency and quality) increases. The quality of the gas and the production speed depend on many parameters. First of all, it mainly depends on the temperature of the digester volume. Gas production increases when the process takes place within one of three specific temperature ranges that form the ideal environment for three different bacteria groups [8]:

- Psychrophilic: $T_{digestate}$ = 20 °C;
- Mesophilic: $T_{digestate}$ = 30 - 42 °C;
- Thermophilic: $T_{digestate}$ = 43 to 55 °C.

In general, the processes at higher temperatures beside retention time also have many other advantages, such as a better elimination of pathogens [8]. However, it also has also some disadvantages. Most domestic biodigester rely on mesophilic microorganisms.

Higher temperatures and retention times lead to better hygiene. For the mesophilic process, which is most frequently used, the AD process leads to a significant reduction of pathogens [26]. Although the AD process leads to the breakdown of harmful microorganisms, total reduction of viruses and bacteria cannot always be guaranteed. Therefore, the connection of toilets to the biodigester stays point of attention and a pre-treatment could be necessarily [15]. Nevertheless, studies from the field on different digester types with toilet connection show that the reduction of important pathogens (e.g. E. Coli and legionella) is sufficient according to WHO standards [15].

8.2.2 Biogas properties

Biogas consists of a number of components (Table A 5), of which methane is the most abundant component, followed by carbon dioxide and water. Also, Hydrogen sulphide (H_2S) is present in the gas, causing corrosion in metal elements that are exposed to the gas [8].

Compound	Chemical symbol	Content (Vol.-%)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapour	H_2O	2 (20°C) -7 (40°C)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

Table A 5: components present in biogas and their estimated content. Source: [8]

The methane concentration of the gas and the biogas yield depends strongly on the feedstock (table 37). Cattle manure usually has a low biogas yield, but a high yield of methane [8].

Feedstock	Methane yield [%]	Biogas yield [m³/tFF*]
Liquid cattle manure	60	25
Liquid pig manure	65	28
Distillers grains with solubles	61	40
Cattle manure	60	45
Pig manure	60	60
Poultry manure	60	80
Beet	53	88
Organic waste	61	100
Sweet sorghum	54	108
Forage beet	51	111
Grass silage	54	172
Corn silage	52	202

** FF=fresh feedstock*

Table A 6: estimated biogas yield per type of feedstock. Source: [8]

8.2.3 Domestic Biodigester types

A number of types has been designed, of which the most common ones described in literature on domestic biodigesters are the following types [26]:

- Solid-state digester
- Floating drum digester
- Tubular digester

8.2.3.1 *Solid-state digester*

Solid-state digesters are digesters made out of a solid construction.

The fixed dome digester type is described as the most promising design [26]. The construction (Figure A 2) is a dome made from bricks, in which the gas is stored. It has a relatively long lifespan. Of all the types the fixed dome digester has more potential than other types to be made from local produced materials, such as bricks and clay. Hence, it is assumed that this type has a better local employment effects than other types [26], which is an important benefit taking into account the SDGs. Furthermore, this makes the fixed dome digester easier to repair locally. Therefore, the fixed dome digester is the main type used by biogas programs nowadays.

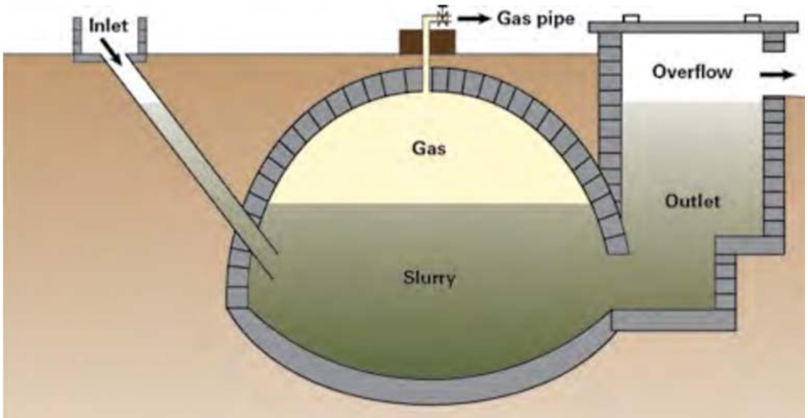

Figure A 2: visualization of the fixed-dome digester type. Source: [26]

Other solid-state digesters are made out of plastic structures.

8.2.3.2 *Floating drum digester*

The fixed dome digester just has a limited gas storage capacity. This problem is solved in a floating drum digester (Figure A 3), where steel drum, mostly made from steel, forms a reservoir that rises when more gas is produced. Therefore, more gas can be stored. However, this type also has a number of disadvantages, such as high installation costs [26].

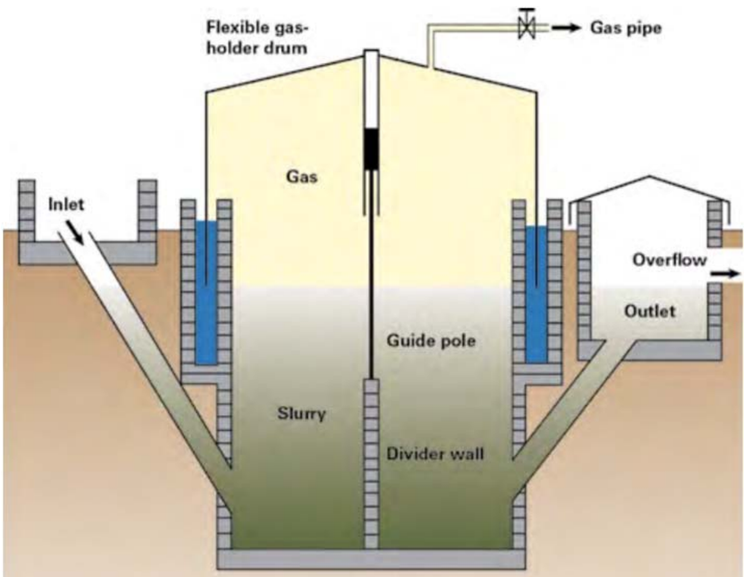

Figure A 3: visualization of the floating drum digester type. Source: [26]

8.2.3.3 *Tubular digester*

Both of the drum digesters require a relatively large and solid construction. This is costly and can be avoided by using a tubular digester (Figure A 4), which is usually a bag made out of plastic. These types are mostly cheaper to buy and easy to install. However the lifespan is assumed to be much lower and it must be imported [26].

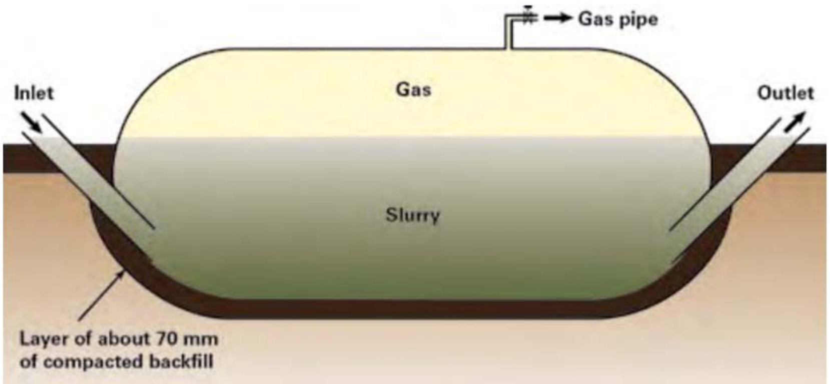

Figure A 4: visualization of the balloon digester (tubular) type. Source: [26].

Examples of tubular digesters that are sold in Kenya include types from Rehau [10] and Biogas International [46].

8.2.3.4 *Adapted digester types*

Since a couple of years also a number of new digester types have entered the marked. New companies try to build digester types that avoid certain local obstacles [22] and creating a new potential for areas that used to be unattractive to the technology. The Dutch company of Simgas constructs a digester type that is built out of 1m^3 prefabricated plastic segments that can be connected to a biodigester with various volumes. Other examples of new digester types that aim to focus on a specific set of conditions are the CAMANTEC from Tanzania, the TED design from Lesotho or the LUPO design from Ethiopia [22]. These respectively focus on lower water consumption, a better suitability for wastewater treatment and a higher gas storage, which can be useful under specific conditions.

8.3 Background of method

8.3.1 Pressure test for detecting leakage

It is a common problem that leakage occurs in biodigesters. It can happen both for bag digesters as solid state digesters. For a number of indicators, it is important that the digesters that are measured are leakage-free [17]. For calculating the specific gas production, it is therefore important that $V_{leaked} = 0$. During the selection of households during the fieldwork sessions in Meru a few households have been rejected for participation in the study, since leakage was detected. For some households, this was not very clear and a pressure test needed to be done.

For a pressure test the pressure of the digester is artificially raised. When the pressure has increased significantly (around + 1 kPa for brick dome digesters) the pressure is observed by pressure gauge to see whether the pressure decreases significantly in the first (around 15 – 30 minutes). When this is the case it means that there is probably leakage. When the pressure remains stable it means that there is no significant leakage.

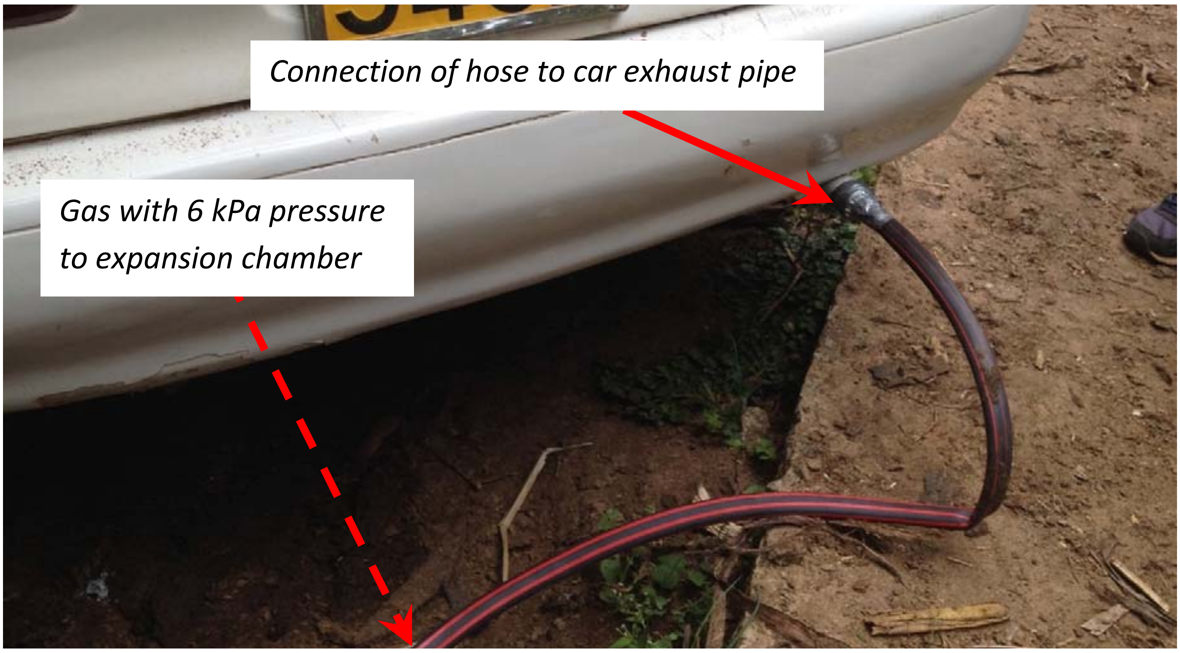

Figure A 5: picture showing a method based on using the car exhaust as pressure test for detecting leakage. Picture from own archieve.

For the pressure tests during the fieldwork in Meru county it was done by leading the exhaust of the car trough the expansion chamber using a garden hose (Figure A 5).

8.3.2 Experiment at Rehau test site

An additional experiment has done during this phase was initiated by Rehau. The company was interested to perform a measuring study to research the effect of the positioning of the plant in the soil to know more about the differences in gas production, pressure and temperature dynamics because of the isolation that the soil provides. Therefore, two digesters with the same properties were monitored under the same daily feeding. Of the two digesters one was covered with soil between wooden plates and the other one has remained uncovered (Figure A 6).

Although the observation provided new information on the use of the data logger for low-pressure biodigesters no conclusions on the experiment could be done, mainly because of the following causes:

- Both digester had to be started up after a forced break due to national elections in Kenya, which took longer than expected.
- The temperature sensor connected to the uncovered biodigester broke down. Therefore, the temperature sensibility of the two digesters could not be compared.
- The uncovered digester did not build op significant pressure. Traces of leakage had been found.

Figure A 6: picture showing the experiment done at the Rehau test site. Of the two identical 3.2 m^3 one is covered with soil (right) to simulate the isolation potential of soil. The other digester is not covered (right). Picture from own archieve.

8.4 Background of results

8.4.1 Problems involved with survey questions

A number of problems were detected with the survey method that was used in this study. An overview is given in this section.

8.4.1.1 *Scale answers for survey questions*

Scale answers were used to create scale data for comparative results. This method did not appear to lead to succesful results. For instance, the following question requires a scale answer.

Are you satisfied with the average gas pressure?

The answer that should be provided should be a number between 1 and 5, where 1 represents no, 5 represents yes. The numbers 2, 3 or 4 are answers that represent a extent of satisfaction in between. Households found it hard to translate their opinion on the gas pressure to a number between 1 and 5. Respondents did also not think about mentioning any answer beside the two outer values 1 and 5 and hence interpreting the question as a binary one. The scale with numbers of one to five did therefore not appear to be a suitable type of question.

8.4.1.2 *Survey question on negative aspects from biodigester*

Remarkably, respondents had difficulties with naming any disadvantages of the biodigester in general. At first most of them tend to focus on the positive aspects of the biodigester, instead of naming negative points or praising the technology in general. In terms of score respondents only wanted to mention the contribution of the biodigester and attach a score of ''1'' (Low negative influence on your life). In-depth questioning provided more accurate information on the opinion of the owner on the ease of use of the digester. However, it still had to be explained multiple times and clarified that the survey was not part of business of the corresponding BCE before the owners were prepared to discuss the negative aspects of the biodigester. Furthermore, examples of negative aspects had to be provided to the respondent in some cases, before the respondent was thinking about negative aspects.

Another negative experience with the formulation of the question is that the concepts of ''habits'' or ''lifestyle'' have debatable definitions, risking answers with a wide variation interpretations.

8.4.2 Problems involved with data logger

As described in the result section many problems were reported that concern the operation of the data logger.

8.4.2.1 *Pre-measuring phase*

The data logger has a lot of transport requirements, because the data logger is quite a large devise. Transporting by motorbike is problematic, when also the solar panel, battery and tools needs to be transported.

Leakage within intra-data logger piping was detected during the installations multiple times. It was in most cases easy to detect, by adding a soap-water mixture and checking for bubbles and reconnecting certain junctions or pipes. In one case, it took a number of hours and only replacing certain tubes solved the problem after a second visit. Most leakage occurred in the internal piping, e.g. the ones that connect the desulfurizer to the flow meter. Other leakage occurred in the hose pipes that connect the data logger with one of the ends of the piping.

Hosepipes are the only solution of connecting the data logger ends with the piping. The disadvantage is that these hosepipes tend to kink when they are bended (Figure A 7), increasing the resistance of the device and leading to a reduced flame. With some improvised tools such as duct tape the hosepipes had to be reinforced to reduce the kinking.

Figure A 7: picture showing kinking of the hoses that are used to connect the data logger with the biodigester piping. Picture from own archieve.

There were difficulties involved in finding a good place for mounting the data logger board, because the data logger needs to be installed close to a spot in the piping where the pipe can be cut for connecting the data logger.

Figure A 8: examples of the positioning of the data logger for biodigester 6 (left) and 3 (right). The position of the solar panel is marked by a yellow circle. The red circle shows the spot where the biodigester piping is interfered for connecting the data logger. The blue circle represents the location of the expansion chamber, where the temperature sensor is inserted. Picture from own archieve.

The temperature sensor cable was also a limiting factor for the placing of the device. In some cases, there was barely enough remaining cable to insert the sensor in the outlet canal. A third factor is the placing of the battery box and solar panel. The cable for this connection is relatively long, but can still be a limiting factor when the sport is very shady. A most cases a solution were found to mount the data logger in a suitable spot. Examples are shown in Figure A 8.

Another place that concerns the location is the fact that the data logger is vulnerable to theft and positioning in an area out of sight from external areas is important. During the fieldwork in Karatina the optimal positioning of the data loggers was to be found too much in sight of surrounding areas, in the case of the households of biodigester 8 and 9. In both cases, it was decided to mount the data loggers to the kitchen building, in permanent sight of the residents. Therefore, the distance to the digester was too far for the installation of temperature sensors. During the installations in Kampala covers for the data loggers were made, adding up a total of around $75 per data logger. These covers were massive and hard to transport, allowing only one data logger system plus cover being able to transport at once.

As mentioned before, the data logger requires obstruction of the piping by cutting (Figure A 9). When connecting an electric welding device is required with the corresponding fittings. Most BCEs poses this type of device and know how to connect. The problem however is that electricity is not always available or too far away from the position where the cable needs to be welded, creating an obstacle for the installation of the data logger.

Figure A 9: example of a welded connection of the biodigester piping (left) to the hose that connects with the data logger (right). Picture from own archieve.

The connection pipe from one of the pressure sensors broke. Eventually it was possible to fix the junction with so-called super-glue, in Kenyan plumbing a popular method of repairing broken plastic and metal parts by liquid glue and an improvised powdery substance such as corn starch or sand.

8.4.2.2 *Measuring phase*

In most cases this was due to the fact that the batteries were at least 3 years old and that their performances were insufficient for powering the data logger. Replacement of the battery solved this. However, some power cuts occurred during the measuring period. In one case one of the replaced batteries did not suit the electrodes and an improved electrode needed to be made at the site. During a later check, it was discovered that the data writing was interrupted because a cable between the battery and the solar panel was not connected, which has probably been a lack of attention. In one case the voltage was highly decreased to due to dust on solar panels, almost causing interruption of data writing.

The data logger in Kampala failed to write data on newly purchased flash disks. The problem was eventually solved by erasing the memory to another extension, but unfortunately three days of records were not recorded.

There was a high frequency of issues with the temperature sensor cut. In total 3 out of 6 data loggers experienced interruption of the temperature data during the total measuring period. One temperature sensor stopped working between de-installation in the Meru area and installation in Juja. Another sensor was interrupted suddenly without clear reason during its measuring in the Meru region. Another temperature sensor was cut by a cow that was grazing around the biodigester, although efforts were done to fence off the terrain around the data logger.

Some data loggers showed problems with the flow meter. For multiple data loggers the flow meter did not work while placed in a certain position, although mounting the data loggers vertically in most cases solved this problem. One data logger however occurred interruption also after correct mounting, without clear reason. After decommissioning the mechanical part of the counter the logger was working again. After the first check, it seemed that the flow meter had not recorded any flow data though. After another decommissioning and change of the position the data logger started working again. It remains unclear what creates the failure, but is it an obvious weakness to the process and it has led to the missing of one week of flow data.

8.4.2.3 *Analysing data*

The CSV files all seem to have their own way of writing the .csv files data regarding time and date. The time is calibrated well for none of the data loggers and the calibration correction is for none a round number of hours, due to for instance difference in time zones between the current location and the location of calibration. From the 6 data loggers in Kenya 3 data loggers had a correct date and incorrect time and 3 data loggers had both incorrect times and incorrect dates. The recorded dates sometimes jumped back to 1/1/2015, but in some cases the records went back to 0/0/00 unexpected. Since one .csv file is written at least every week and interrupted recording sometimes lead to the creation of new files it is a lot of data puzzling efforts and errors. An example is given in Figure A 10, which shows the recorded files from biodigester 4.

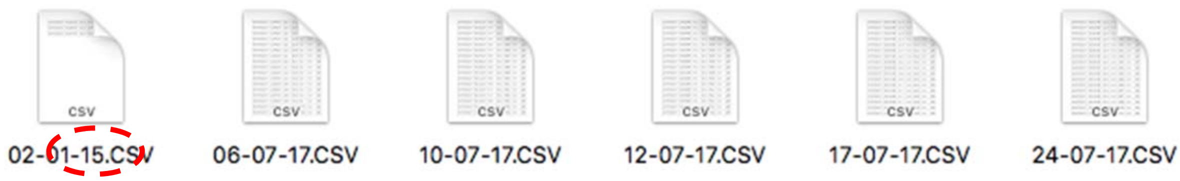

Figure A 10: example of incorrect datarecords of the files produced by one data logger.

8.4.3 Logistics as limiting factor to data collection

Experiences from fieldwork sessions show that logistics required to visit famers are the main obstacle of good process scores. This includes application of the survey, logbook, data logger. A number of aspects are important:

- Visiting a number of households in one day from the central base of the fieldwork region is limited due to the quality of the roads, the findability of the locations and the time involved in the visit itself. Although households were selected that are located near another (which was the case for the fieldwork sessions in Meru county), the limited households to visit in one day was around five to six.
- There is usually no public transport around that lead to the locations and therefore private transport is required for every day of fieldwork.
- To bring the data loggers to the central base in the fieldwork region private transport is required, since the data loggers are too large to be transported by public transport.

Altogether, logistics are responsible for the majority of the time and financial requirements, affecting the process scores. When international transport of the data loggers between ABPP countries is included, logistics even get a more crucial factor.

8.4.4 Dung & water balance

Since both underfeeding and overfeeding can lead to lower specific biogas production it is recommended to follow the feeding prescriptions provided by ABPP (HRT = 50 and water/dung-ratio = 1:1 [24]). One measure for the effect of underfeeding and overfeeding as one measure is to express the actual feeding as a deviation from the advised value in absolute terms. This so-called feeding balance is proposed as measure for (in)stability due to feeding:

Feeding balance = $| M_{unmixed\ dung} / M_{dung\ advised} - 1 |$

This implies that with a recommended feeding of $M_{dung\ advised}$ = 50 kg / day and an actual feeding of $M_{unmixed\ dung}$ = 100 kg, the balance is (+100%). When $M_{unmixed\ dung}$ = 25 kg / day the balance is (-) 50. The results of this method are shown in Table A 3.

Dung		1	2	3	4	5	6	8	9
SGP	l/kg d.	36.2	10.2	31.9	20.7	28.7	21.6	24.9	35.4
Dung Feeding	Kg / day	100	112	39	100	40	41	75	33
Dung advised	Kg / day	100	80	60	80	80	80	80	40
Balance	% (a)	0%	+40%	-35%	+25%	-50%	-49%	-6%	-18%

Table A 7: overview of the dung balance for the six brick dome digesters in Meru county and the two Simgas digesters in Nyeri County.

The water balance was calculated by the same method of calculating the dung balance. However, $M_{water\ advised}$ corresponds the amount of water that is advised to feed based on the actual feeding of dung, since the actual dung water ratio in comparison to the advised ratio is desired. Hence, $M_{unmixed\ dung} = M_{water\ advised}$ and the following formula describes the water balance.

Water balance = $| M_{water} / M_{water\ advised} - 1 |$

The results are shown in Table A 8.

Water		1	2	3	4	5	6	8	9
Water feeding	Kg / day	141	886	357	410	80	193	776	230
Water advised	Kg /day	100	112	39	100	40	41	75	33
Balance	% (b)	(*[a])	+122%	-15%	-27%	-50%	-66%	+39%	-18%
([a]) This number is excluded because water was added to the the dung of the household before mixing.*									

Table A 9: overview of the water balance for the six brick dome digesters in Meru county and the two Simgas digesters in Nyeri County.

One disadvantage of this approach is that underfeeding the imbalance due to underfeeding is rated relatively mildly. An alternative approaches can be made that represent this more precize.

8.4.5 Methods for determining the surface requirements

The first method (Figure A 11) is to measure the surface by including the area of all component in one rectangular figure. A problem with the first mentioned methods is that the width of the widest element is used as width whole system. That means that the total surface is quite overestimated. Another issue is that the slurry pits are not available at every system, dependent on the preferences of the customers. They easily occupy a significant number of square meters, leading to an overestimation for some of the digester systems in comparison to the ones that do not have slurry pits. Slurry pits are not included in the scope and any type of slurry pit can be matched with any type of digester and can therefore be excluded (method 2).

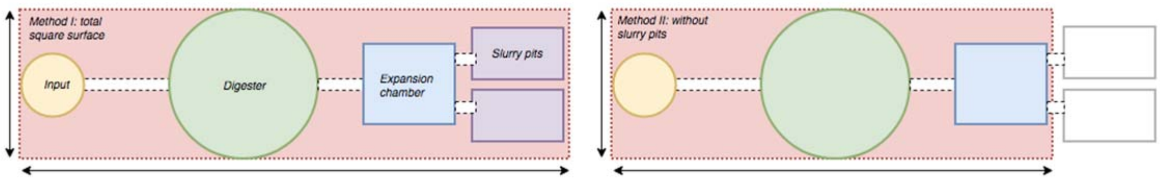

Figure A 11: visualisation of two methods of measuring the digester surface. One method includes the slurry pits. The other method does not.

Another issue is that the input tub is often far from the digester itself, while the tub itself does not occupy much surface. Another method that can be used is to exclude the input (method 3, Figure A 12). Also with this the area between the expansion chamber and the digester is included, although it might be used for other purposes. Therefore another method is to measure all components (either as rectangles or circles) separately and summing up the results.

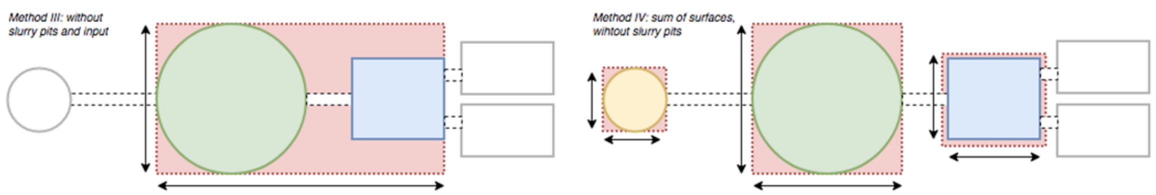

Figure A 12: visualisation of two methods of measuring the digester surface. One method excludes the input and the other method does not.

For the biodigesters in the field an overview of the methods that were used for determining the total surface are given in Table A 10: overview of surface calculations of the measured biodigesters.

Household name	Digester Surface (m^2)	Volume (m^3)	Specific surface (m^2/m^3)	Slurry pits included?	Inlet included?	Method used
1. Igoki	n/a	10	n/a	-	-	-
2. Mutwiri	12.8	8	1.6	No	Yes	2
3. Iguchia	12.1	6	2.0	No	Yes	2
4. Mbaya	13.0	8	1.6	No	Yes	2
5. Muchemi	10.9	8	1.4	No	No	4

6. Kiambi	16.8	8	2.1	No	Yes	2
7. Kampala	n/a	8	n/a	-	-	-
8. Mari	9.8	8	1.2	No	No	3
9. Kibui	7.0	4	0.9	Yes	Yes	2
10. Rehau cov.	6.5	3.2	2.0	No	Yes	4
11. Rehau unc.	6.5	3.2	2.0	No	Yes	4
12. Blueflame	3.8	3.2	1.2	No	Yes	4

Table A 10: overview of surface calculations of the measured biodigesters.

8.5 Background of discussion

The process scores for all data loggers are presented by Table A 11, assuming the weighting factors as explained in section 3.2.2.

Regular WF	Simplicity	Intervention	Affordability	Time	**Weight. total**
Weighting	50%	10%	20%	20%	**100%**
Database	5	5	5	5	**5**
Survey	4	3	3	3	**3.5**
Logbook	4	1	2	2	**2.9**
Data logger	1	1	1	1	**1**
Observation	4	1	3	2	**3.1**

Table A 11: overview of scores for aspects of different measuring tools, including weighted scores.

The first alternative scenario (section 5.3.1.2) based on the large-scale application of the measuring tools, the affordability and time requirements become more important. The scores that result from this alternative approach are given in Table A 12.

Large scale WF	Simplicity	Intervention	Affordability	Time	**Weight. total**
Weighting	10%	10%	50%	30%	**100%**
Database	5	5	5	5	**5**
Survey	4	3	3	3	**3.1**
Logbook	4	1	2	2	**2.1**
Data logger	1	1	1	1	**1**
Observation	4	1	3	2	**2.6**

Table A 12: overview of scores for aspects of different measuring tools, including weighted scores for weighting factors adapted to large scale performance measuring

Table A 13: overview of scores for aspects of different measuring tools, including weighted scores for weighting factors adapted to the minimization of intervention.

The scenario based on the situation where the extent of intervention on the household should be minimized leads to the scores presented in Table A 13.

InterventionWF	Simplicity	Intervention	Affordability	Time	**Weight. total**
Weighting	30%	50%	10%	10%	**100%**
Database	5	5	5	5	**5**
Survey	4	3	3	3	**3.3**
Logbook	4	1	2	2	**2.1**
Data logger	1	1	1	1	**1**
Observation	4	1	3	2	**2.2**

8.5.1 Scenarios for selection of measuring tools

The final data quality scores are presented in Table A 14.

	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GC								
Database						2.5				5
Survey		1	3			**4**	**4**	1	2	3.5
Logbook	**4.5**	2.5								2.9
Data logger		**4.5**	**4**	**4**	**4**					1
Observation	3.5	1	2				3	**1.5**	**4.5**	3.1

Table A 14: overview of process scores in case of a high importance of intervention.

The selection of measuring tools that would be selected based on the best data quality is presented by Table A 15.

Scenario 1: Best records	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GP								
Database										5
Survey						**4**	**4**			3.5
Logbook	**4.5**									2.9
Data logger		**4.5**	**4**	**4**	**4**					1
Visual Observation								**1.5**	**4.5**	3.1

Table A 15: overview of the data quality and process scores for the best records method

The selection of measuring tools that would be made based on the preference for using visual observation and the ABPP database is presented in Table A 16.

Scenario 2: Observation	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GC								
Database						2.5				5

Survey										3.5
Logbook										2.9
Data logger		**4.5**	**4**	**4**	**4**					1
Visual Observation	3.5						3	**1.5**	**4.5**	**3.1**

Table A 16: overview of the process scores for the scenario based on visual observation and the database.

The selection of measuring tools that would be made based on the preference for using the survey is presented in Table A 17.

Scenario 3: Survey	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GC								
Database										5
Survey						**4**	**4**	1	2	3.5
Logbook	**4.5**									2.9
Data logger		**4.5**	**4**	**4**	**4**					1
Observation										3.1

Table A 17: overview of the process scores for the scenario based on surveys and thereby excluding observation.

The selection of measuring tools that is made when the input of dung is standardized for every households, making the logbooks unnecessary, is presented in Table A 18.

Scenario 4: Stand. dung	1 SGP		2 GP	3 GPS	4 GSV	4 IC	6 EoU	7 Rb	8 RS	Process
	1a DI	1b GC								
Database										5
Survey						**4**	**4**	1	2	3.5
Logbook										2.9
Data logger		**4.5**	**4**	**4**	**4**					1
Observation										3.1

Table A 18: overview of the process scores for the scenario based on exclusion of the logbook and using the survey.

8.5.2 Advantages of performance measuring for BCEs

A number of advantages were mentioned by BCEs. Performance measuring can provide useful information for them about the strengths and weaknesses, which can be used for e.g. the evaluation of digester models or better advice on feeding. However, the major advantage of performance measuring for BCEs by GPRS-connection is that it provides a live track of the biodigester performance [47,48]. When the feeding is unbalanced after-sale-service can be directed immediately to the households that need it. Another benefit from performance measuring for BCEs is that there is evidence on the performance and user behaviour of the digester owner. For purchasing biodigester on credit the main risk are defaulters, that often argue that the digester did not perform as indicated although they fed the digester correctly. These arguments can be refuted with clear figures when the owner brings in unfair arguments, which could take away a part of the risks of credit systems

8.5.3 Costs and time indications for measuring tools

An estimation of the costs and time requirements per measuring tool was made (Table A 19), which was used as basis for the indication of affordability and time described in section 4.1. The expenditures done in the fieldwork of the Meru study have been used as reference, since this fieldwork phase was the most comprehensive. Also, an estimation of time requirements are made, presented in Table A 21. The investment costs required for alternative measuring tools and the shipping costs estimations of all data logger types are given in Table A 20.

8.5.3.1 *Cost estimations*

It is important to note that these indications are only indicative and provide no guarantee for the costs and time requirements of future studies. The following notes must be taking into account when these indication are used for quantitative purposes:

- The cost estimation is made on base on average prices in central Kenya and are likely to be different for other areas or countries.
- Hotel costs and other costs of living the researcher is likely to make during fieldwork sessions are not included.
- The expenditures on assistance and local transport are highly dependent on distance between the biodigesters of the field study. Higher distances means that less visits can be done and thus more days of fieldwork are required. For the Meru fieldwork the radius of the area was approximately 15 km.
- The expenditures on in and out transport are highly dependent on the distance of the research area to the headquarter. For the Meru region this was a travel distance of around 6 hours.
- The costs and time requirements include the numbers per separate measuring tool. Applying different measuring tool on one selection of household is probably to safe many costs in assistance and transport.
- Shipping of the data loggers is a very unsecure estimation based on an indication of one interview. Pronon indicated shipping costs of $1350 to send 6 ABPP data loggers by international transport [37] and it is assumed for half of the studies shipping is assumed to be required. The distance of sending is very dependent on these costs.

Costs ($) based on 6 households	KBP database	User Survey	Logbook	Data logger	Visual observation		Phone survey	Updated database	Data logger 2.0 / 2.1 / 2.2
O&M	0	0	0	50	0		0	0	100
Assistance	0	25	50	150	25		0	0	150
Household rewards	0	0	75	50	0		0	0	50
In / out transport	0	20	40	250	20		0	0	40
Local transport	0	30	60	180	30		0	0	60
Subtotal	**0**	**0**	**225**	**680**	**55**		**0**	**0**	**400**
Shipping	0	0	0	675 (b)	0		0	0	225

Investment	0	2	5	0	10		0	0	661 – 1015 [(a)]

[(a)] Investment costs depends on the type of installed flow meter and manufacturer.
[(b)] Shipment costs are based on the assumption that international transport is required for halve of the field studies

Table A 19: Cost indications of the process of using different measuring tools and investment

The following costs are indications for a the development of a new data logger type. The indications have been retrieved from :

- For the Simgas data logger 2.0, 2.1 and 2.2 the indications are given in an interview with Simgas technical staff [47,48]. Note that only a few dozen of data loggers have been produced, so the costs are just rough estimations.
- For the ABPP data logger (2014) and the data logger 2.2 by Pronon, indications were given by the developer from Pronon [37]. The indication of the total costs for the data logger from 2014 is accurate. The estimation for data logger 2.0 is a rough estimation.
- The size of a new data logger would be much smaller, approximately one-third [37] of the volume and therefore one third of the shipping costs was assumed for the second generation dataloggers.

Costs each (n = 50 - 100)	Manufacturing costs €	Flow meter €	Subtotal €	Shipment €	Total €	Total $ ([b])
ABPP data logger (2014)	1350	Incl.	1350	1350	2700	3132
Data logger 2.0 by Simgas	120	n/a	120	450	570	661
Data logger 2.1 by Simgas	120	10	130	450	680	789
Data logger 2.2 by Simgas	120	200 ([a])	320	450	770	893
Data logger 2.2 by Pronon	375	Incl.	375	450	875	1015

[(a)] The price indication provided by Pronon for the quality flow meter (€200) was used to estimate the costs for the data logger 2.2 made by Simgas.
[(b)] Exchange rate of 1.16 $/€, 8/11/2017)

Table A 20: cost indications for existing and proposed data loggers by Pronon and Simgas.

8.5.3.2 *Time requirement estimations*

The following additional notes must be taken into account for the time requirements:

- Analysing data includes the processing of the data in excel, checking on errors and making the desired figures.
- A check-up for the data logger needs to be done for every two weeks of measuring

Time (days) based on 6 households	KBP database	User Survey	Logbook	Data logger	Visual observation		Phone survey	Updated database	Data logger 2.0 / 2.1 / 2.2

Installing / removing	0	0	3	6	0		0	5	6
Check-ups	0	1	0	3	3		0	0	0
In / out transport	0	1.5	3	4.5	1.5		0	0	3
Analysing data	1	1	2	10	2		1	1	4
Subtotal	**1**	**3.5**	**8**	**23.5**	**6.5**		**1**	**6**	**13**

Table A 21: time requirements for using measuring tools.

8.5.4 Overview of biogas expert results

Two questions of the biogas expert survey included open questions for suggestions of performance indicators that were not included in this study.

The first question focussed on performance indicators of the biodigester only. The following suggestions were made:

- Impact on local economy / local entrepreneurs and technicians;
- Use of construction materials;
- Water requirements / maximum organic loading rate / ability to use different substrates;
- Minimum HRT;
- Brand confidence, aesthetics (e.g. modern feel), automatic feeding;
- Transportability;
- Ease of repair.

In a second question the quality of the BCE as an enterprise was asked. A number of suggestions were already given in a survey question (quality of the biodigester, quality of after-sale-service, availability of credit systems for purchasing a biodigester, quality of additional biogas products it offers and the installation time of the biodigester. The following suggestions were done by the respondents:

- Service and support provided by supplier;
- Perception of professionality;
- Quality of pre-sales information;
- Networking capacity of BCE and partnerships with development programs;
- Costs of materials (sourcing);
- Explanation on bioslurry use;
- Awareness of cultural context of potential users;
- Quality of biogas appliances and their compatibility with the biodigester;
- Profit margins of digester types;
- Combined business and technical understanding;
- Proactive education, capacity building and monitoring.

8.6 Calculations

8.6.1 Conversion of pressure units

The ABPP uses cm H2O as pressure unit. In other biogas literature kPa and mbar are often used as units. For the comparison with atmospheric pressure a calculation from or to atm is sometimes required. The conversion factors are given in Table A 22.

Cm H2O	*kPa*	*mbar*	*Atmosphere*
1	0.09807	0.9807	0.0009678
10,20	**1**	10	0.009869
1,097	0.1	**1**	0.0009869
1033	101,3	1013	**1**

Table A 22: conversion factors of different pressure units. Source used: [49]*.*

This suggests that roughly 1 cm h_2O equals 0.1 kpa, 1 mbar and 0.001 atm.

8.6.2 Pressure calculations

8.6.2.1 *Volume versus normal volume*

The volume that flows through the flow meter under a certain pressure is slightly compressed and leads to lower records than the same quantity of gas would record under atmospheric pressures (Nm^3). To calculate the normal volumes the absolute volumes (m^3) the volumes should be corrected for their pressures.

The ideal gas law [49] is described as:

$pV = nRT$,   where n represents the gas quantity in moles, R is the ideal gas constant.

The volume that volume V1 with pressure p1, according to the ideal gas law would occupy under atmospheric pressure:

$V_{p0} = V_{p1} * P / P_{p0}$ where p_0 represents atmospheric pressure.

With a digester pressure of 5 kPa (roughly 0.05 atm, appendix 8.6.1)), the recorded volume should be corrected with a factor of 1.05 atm / 1.00 atm = <u>1.05</u> to calculate the normal volume accuractely.

8.6.2.2 *Gas flow through two data loggers in series*

The ideal gas law [49] is described as:

$pV = nRT$, where n represents the gas quantity in moles, R is the ideal gas constant.

Without leakage (Δn = 0) and constant temperature (ΔT=0) we can assume that:

$p_{DL1}V_{DL1} = p_{DL2}V_{DL2}$,   where DL1 represents the first data loggers of the series and DL2 the second.

The maximal theoretical pressure drop that can occur in this system is the biodigester pressure itself relative to the atmospheric pressure, which is maximum 0.8 kPa, according to the measurements of the

Blueflame digester. Adding this to the atmospheric pressure (1 atm = 101.3 kPa, appendix 8.6.1) gives a pressure of 102.1 kPa inside the digester and 101.3 kPa outside of the digester.

Threating biogas as an ideal gas would mean that one m^3 of gas would be 1.008 liters, which means an error margin of 0.8%. This number is obviously an overestimation of the possible drop in pressure. Taking into account the observed variation in flow between the two data logger (14% - 15%) shows that this variation results is in all probability not caused by the pressure drop, but a calibration problem. The possibility that the calibration of the flow meters might be outdated was also confirmed by the developer.

8.7 Raw data from data loggers and logbook

Twelve biodigesters were measured in during the period July – September, of which an overview is given in Table A 23. Not all data was succusfully retrieved, due to a number of circumstances. For some biodigesters the data logger records were interrupted. For others, logbook data was not matching with the same period as the data logger and one logbook was missing. For the last biodigester records were taken using two data loggers. In this section the data records from the full measuring periods of all measured biodigesters are given, including flow data, pressure data, temperature data and the cooking and feeding data from the logbooks.

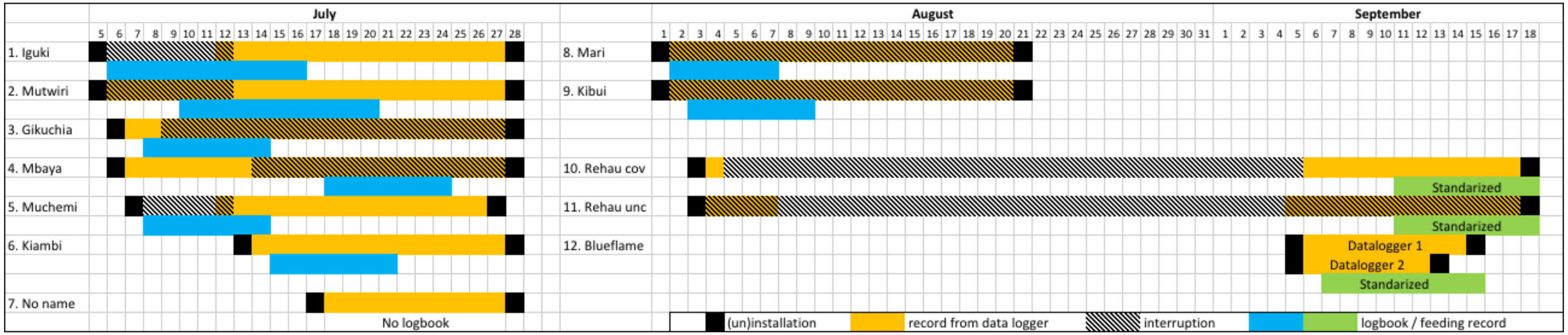

Table A 23: overview of the fieldwork schedule and the data that has (not) been obtained.

In this section the data records from the full measuring periods of all twelve measured biodigesters are given, including:

- flow data;
- pressure data;
- temperature data;
- cooking and feeding data from the logbooks, if available.

8.7.1 Biodigester 1 (Beatrice Igoki)

8.7.1.1 *Pressure data*

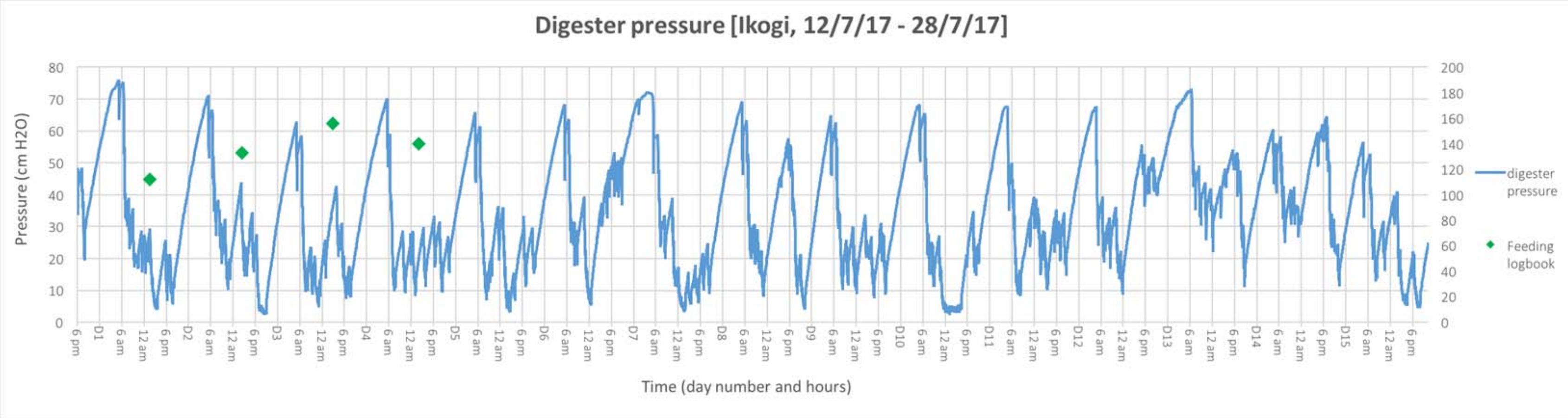

Figure A 13: visualization of digester pressure data of biodigester 1.

8.7.1.2 *Flow data*

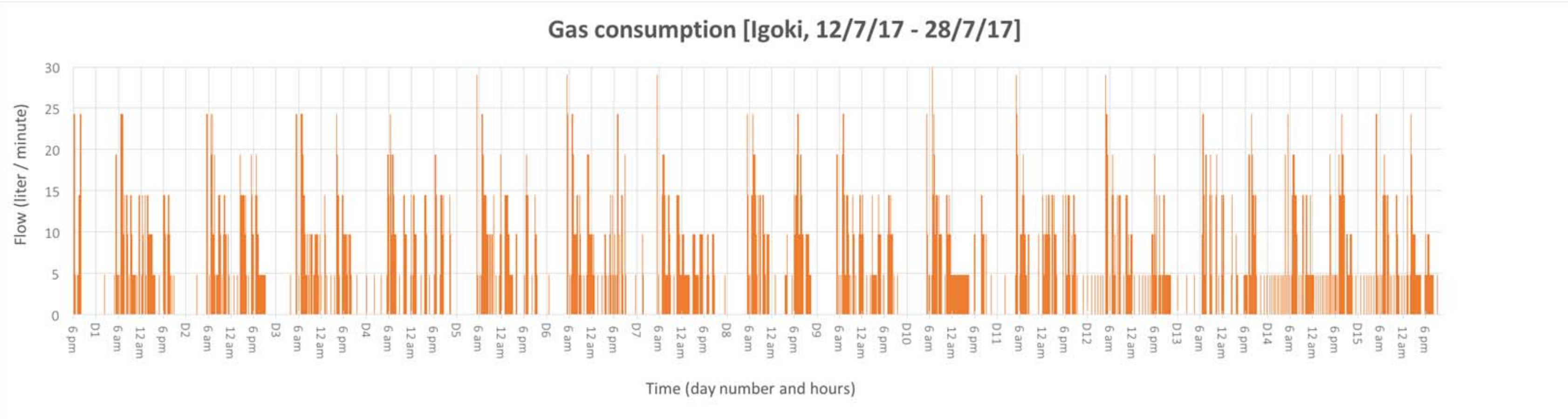

Figure A 14: visualization of flow data of biodigester 1.

8.7.1.3 *Temperature data*

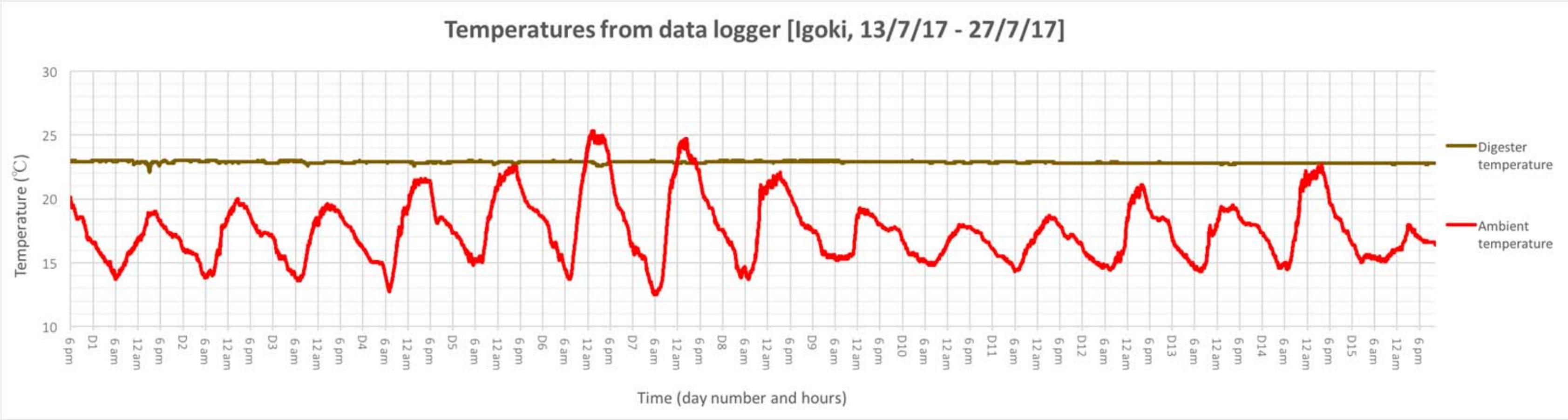

Figure A 15: visualization of slurry and air temperature data of biodigester 1.

8.7.1.4 *Logbook data*

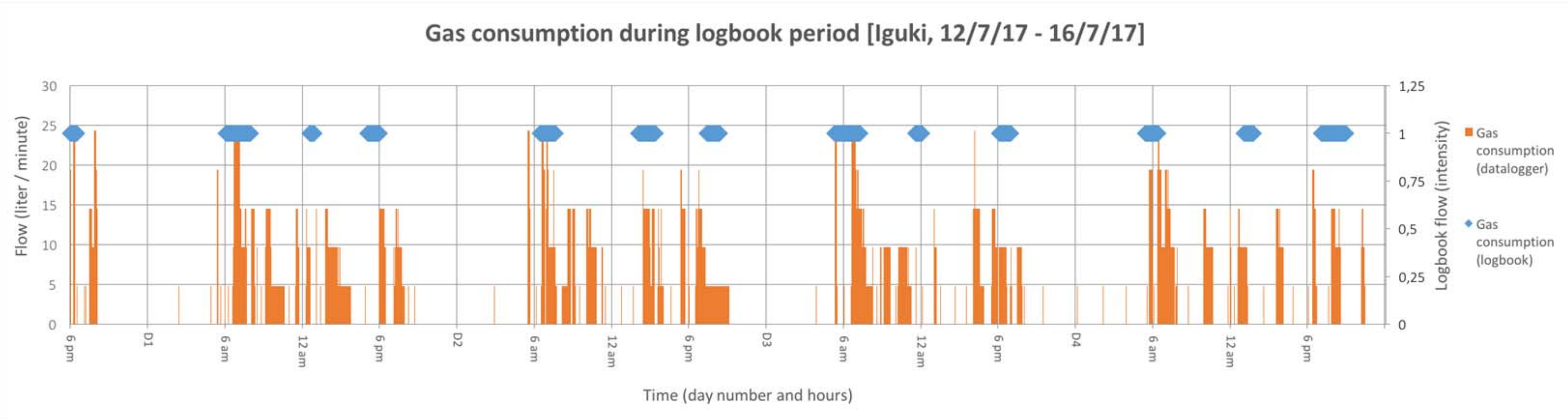

Figure A 16: visualization of flow and logbook data of biodigester 1.

8.7.2 Biodigester 2 (John Mutwiri)

8.7.2.1 *Pressure data*

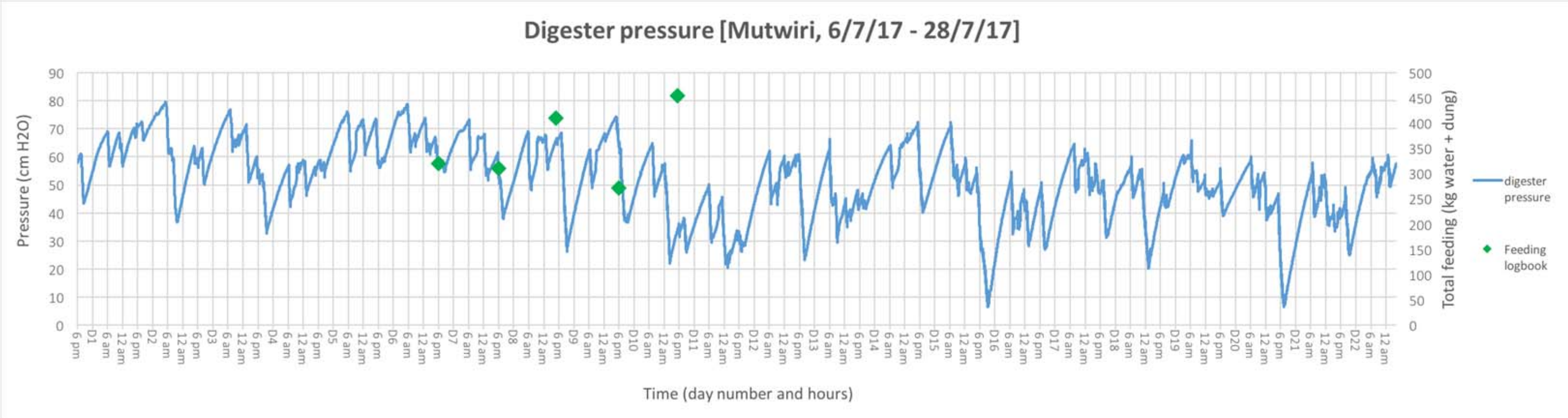

Figure A 17: visualization of digester pressure data of household 2.

8.7.2.2 *Flow data*

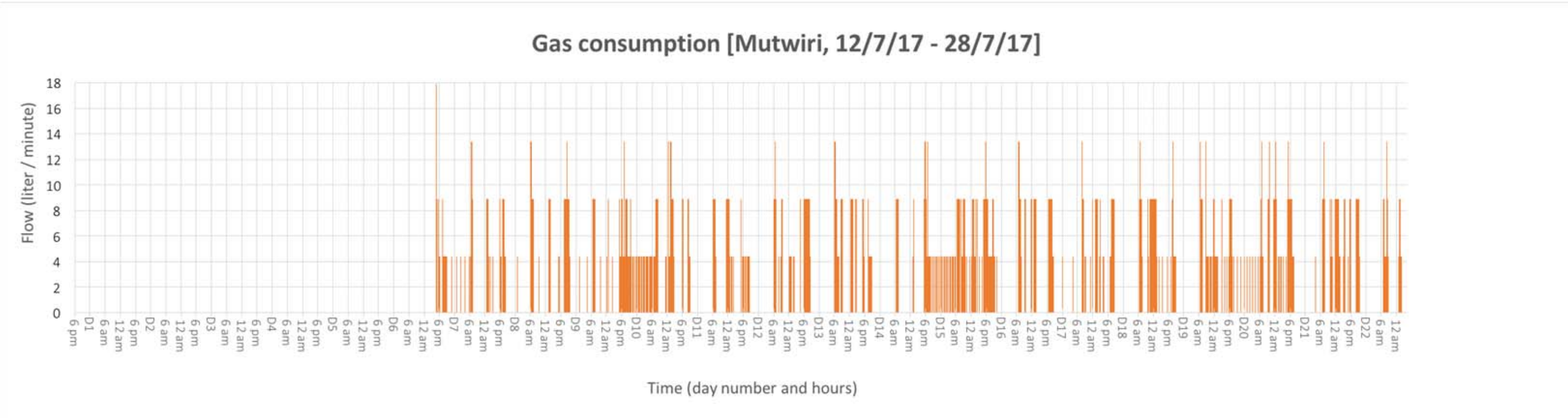

Figure A 18: visualization of flow data of household 2. Note that the flow meter was not working until day six.

8.7.2.3 *Temperature data*

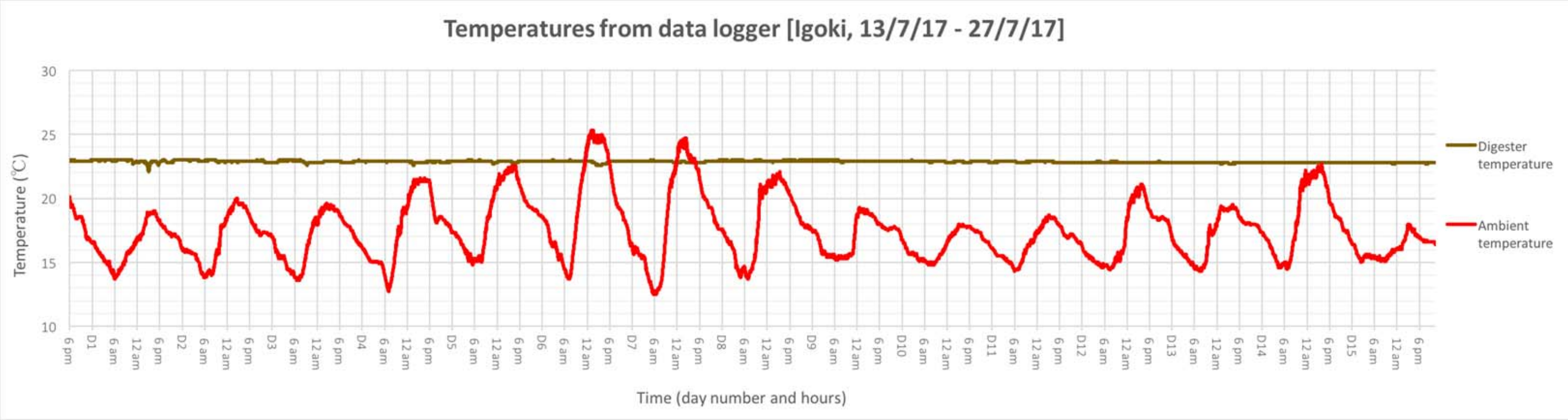

Figure A 19: slurry and air temperature data of biodigester 2.

8.7.2.4 *Logbook data*

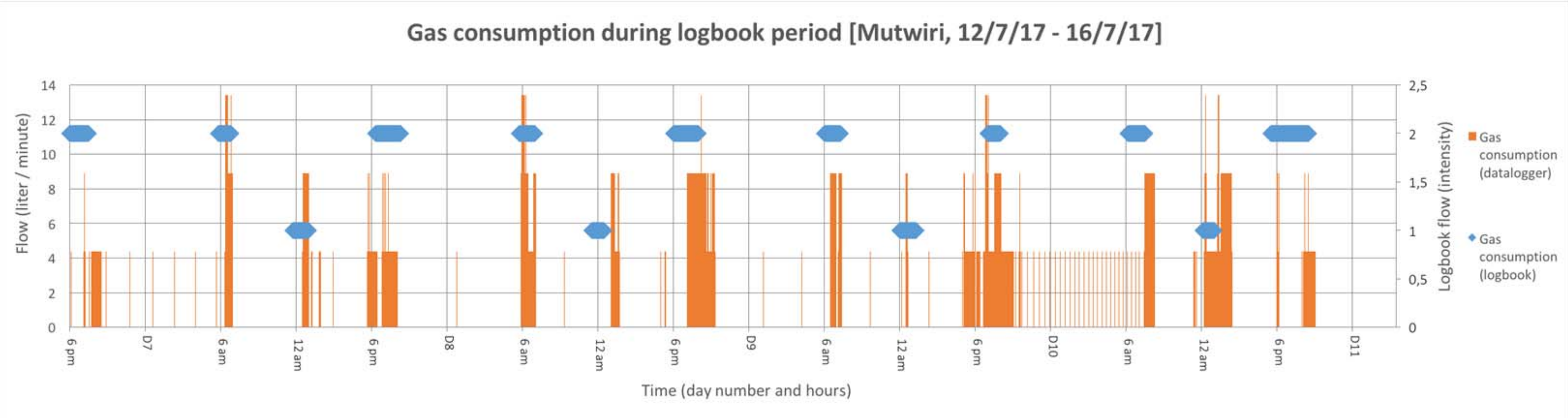

Figure A 20: visualization of flow and logbook data of biodigester 2.

8.7.3 Biodigester 3 (Joshua Gikuchia)

8.7.3.1 *Pressure data*

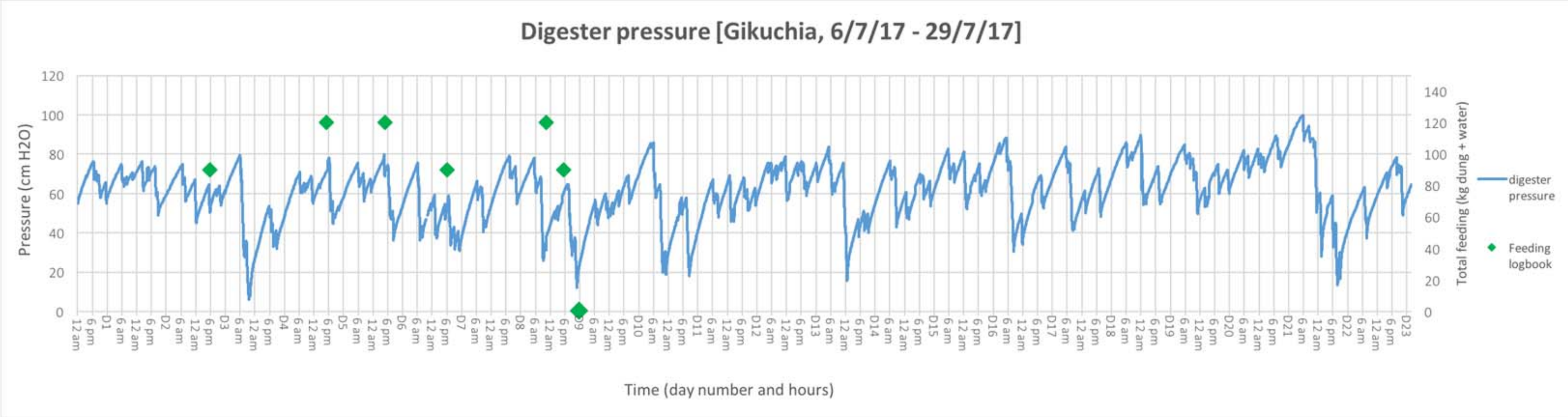

Figure A 21: visualization of digester pressure data of biodigester 3.

8.7.3.2 *Flow data*

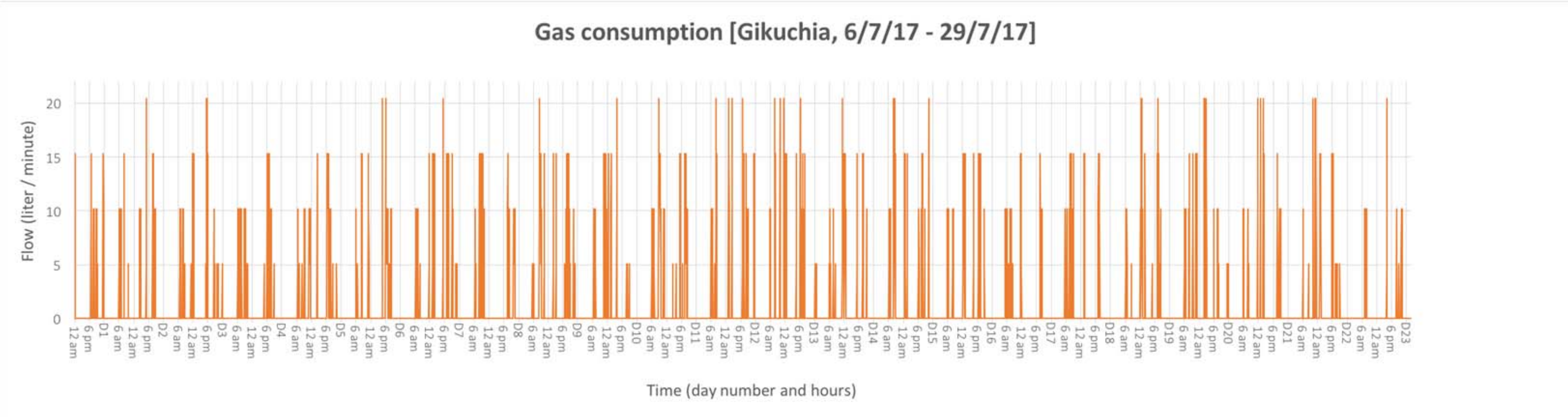

Figure A 22: visualization of flow data of biodigester 3.

8.7.3.3 *Temperature data*

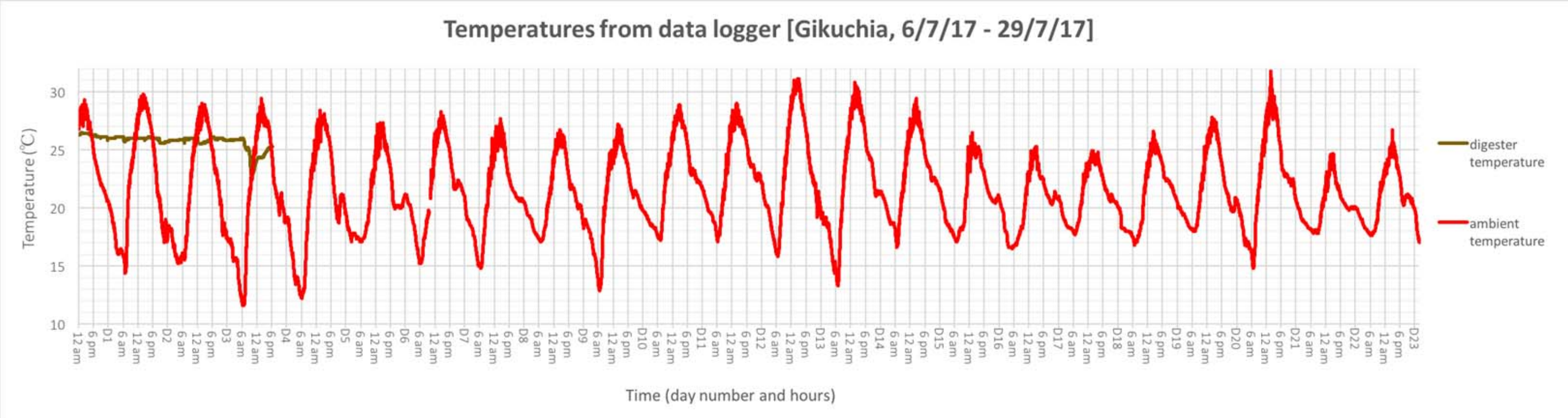

Figure A 23: visualization of slurry and air temperature data of biodigester 3. Note that the digester temperature is only recorded until the end of day three, because the cable of the temperature sensor was cut by one of the cows.

8.7.3.4 *Logbook data*

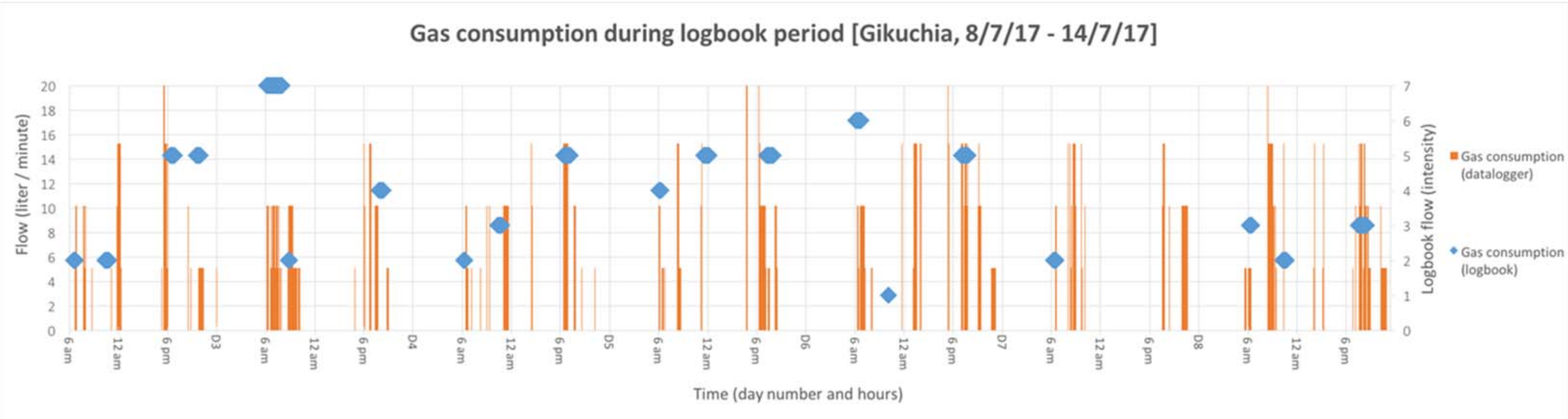

Figure A 24: visualization of flow and logbook data of biodigester 3.

8.7.4 Biodigester 4 (John Mbaya)

8.7.4.1 *Pressure data*

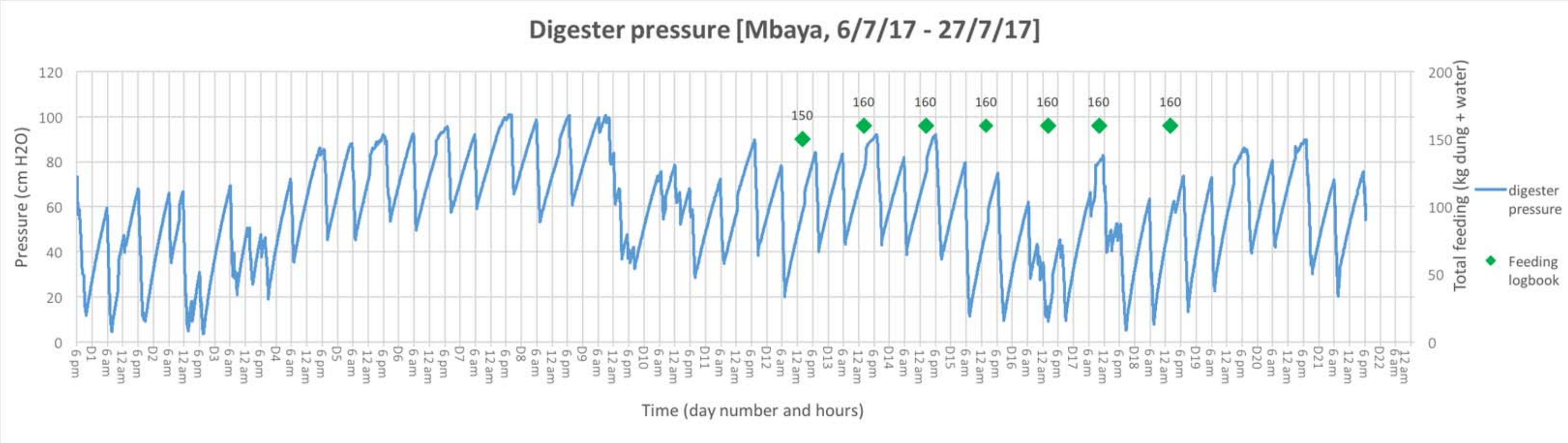

Figure A 25: visualization of digester pressure data of biodigester 4.

8.7.4.2 *Flow data*

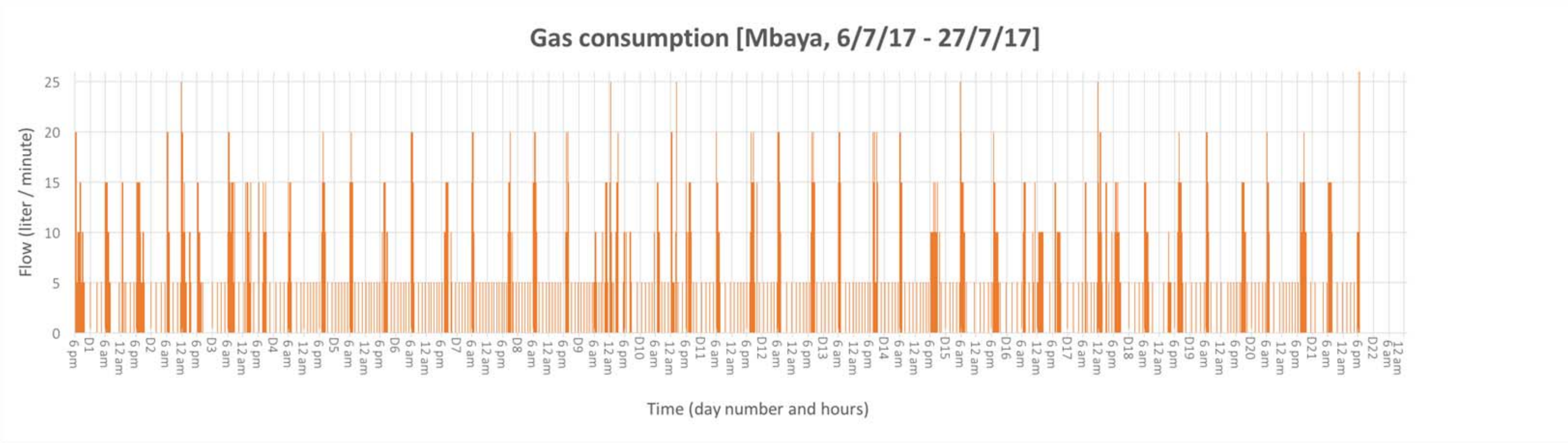

Figure A 26: visualization of flow data of biodigester 4.

8.7.4.3 *Temperature data*

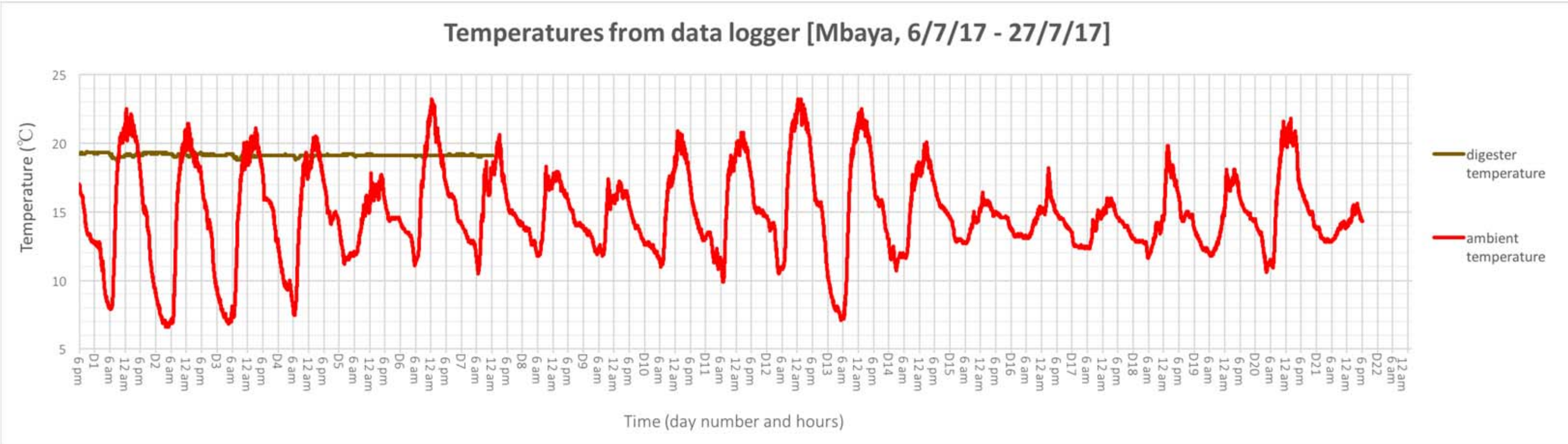

Figure A 27: visualization of slurry and air temperature data of biodigester 4. Note that the slurry temperature is only recorded for a number of days, due to failure of the temperature sensor.

8.7.4.4 *Logbook data*

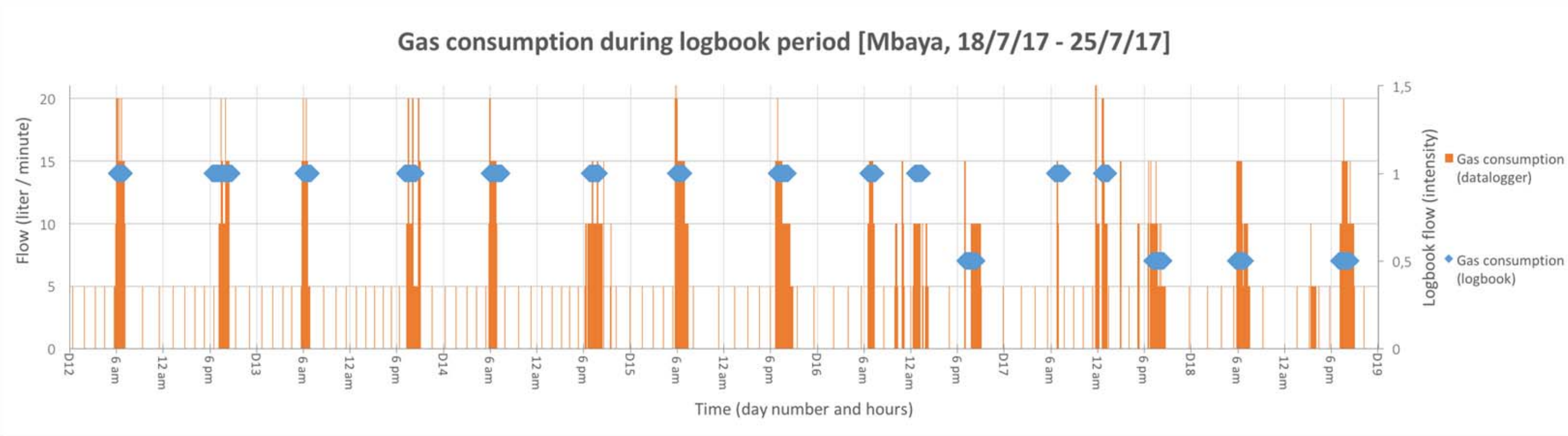

Figure A 28: visualization of flow and logbook data of biodigester 4.

8.7.5 Biodigester 5 (Robert Muchemi)

8.7.5.1 *Pressure data*

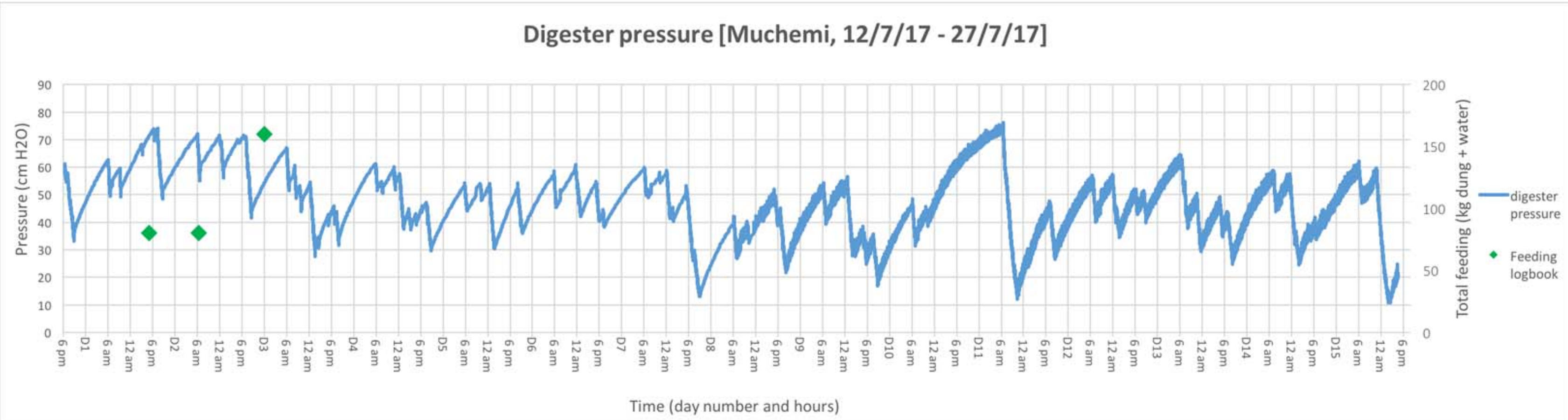

Figure A 29: visualization of digester pressure data of biodigester 5.

8.7.5.2 *Flow data*

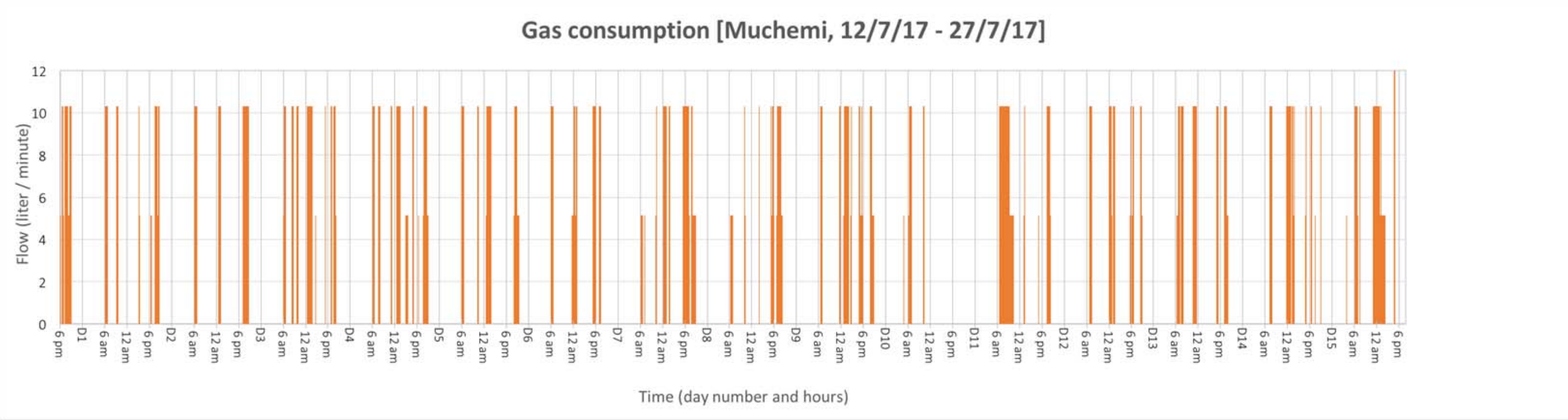

Figure A 30: visualization of flow data of biodigester 5.

8.7.5.3 *Temperature data*

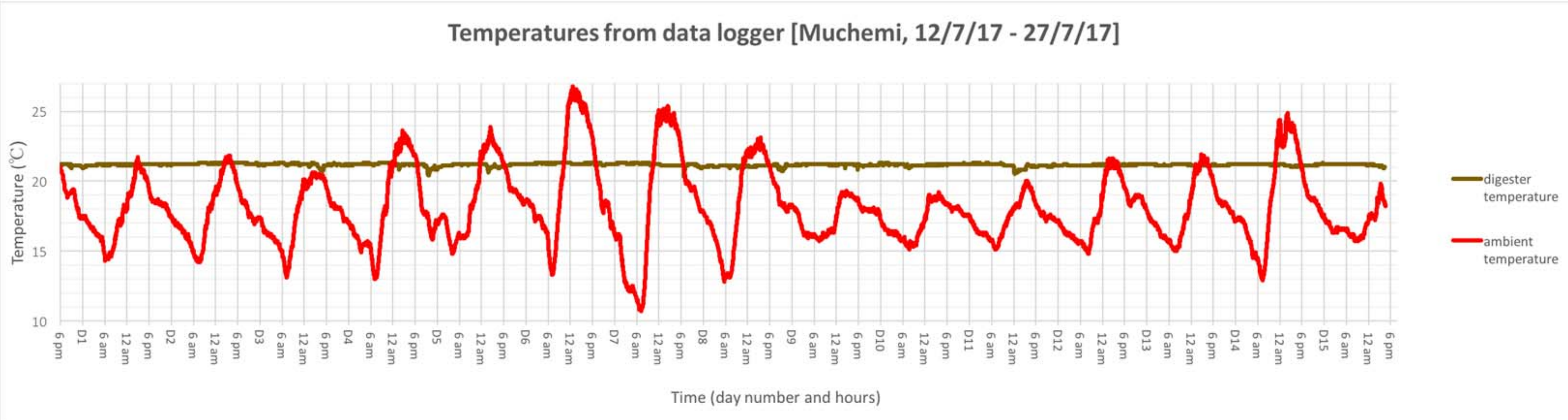

Figure A 31: visualization of slurry and air temperature data of biodigester 5.

8.7.5.4 *Logbook data*

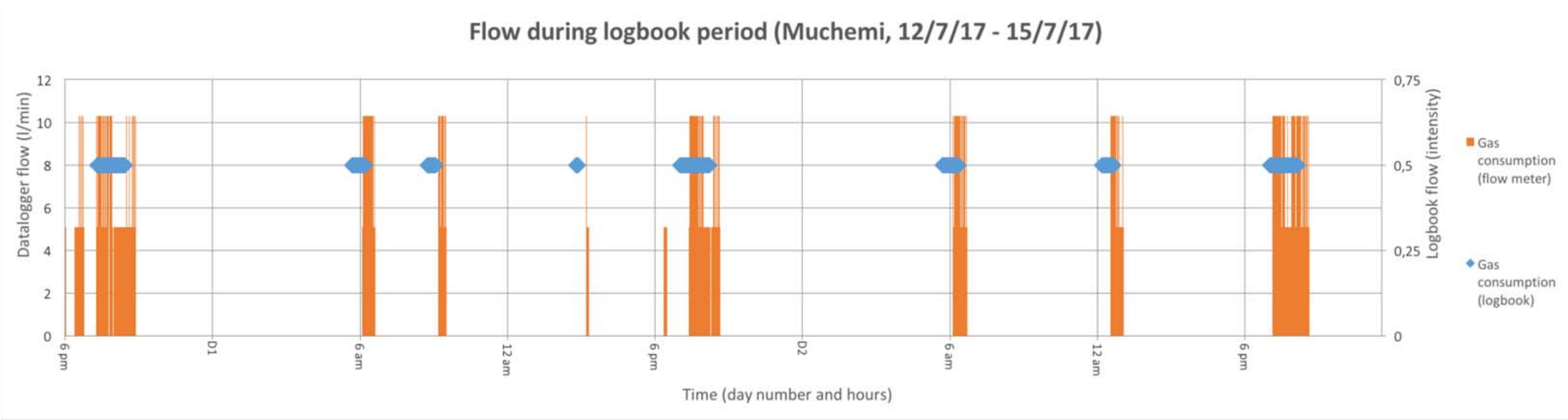

Figure A 32: visualization of flow and logbook data of biodigester 5.

8.7.6 Biodigester 6 (Francis Kiambi)

8.7.6.1 *Pressure data*

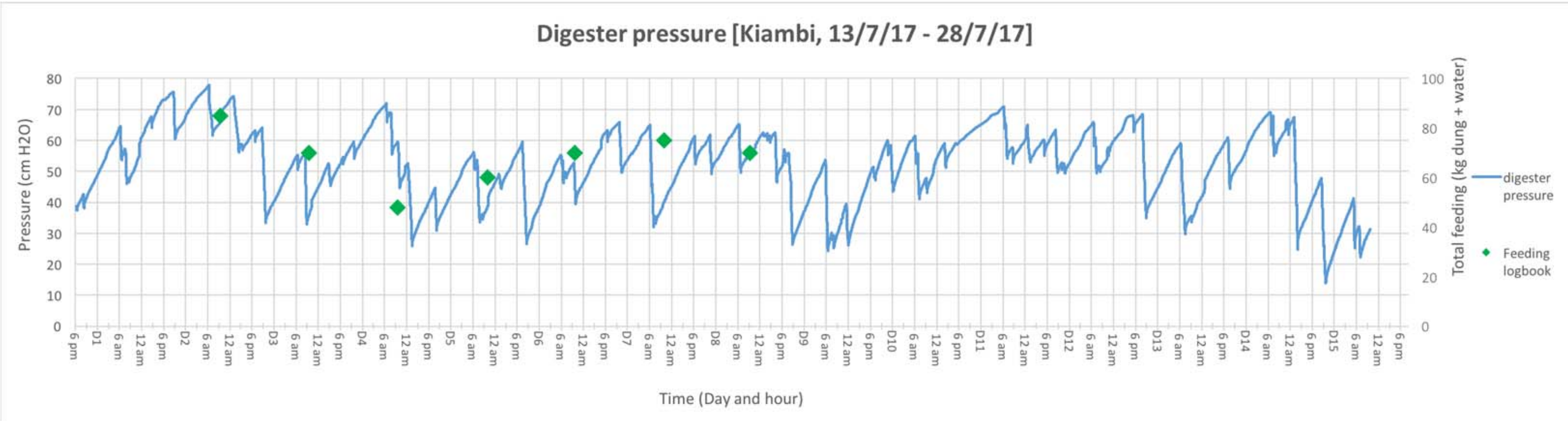

Figure A 33: visualization of digester pressure data of biodigester 6.

8.7.6.2 *Flow data*

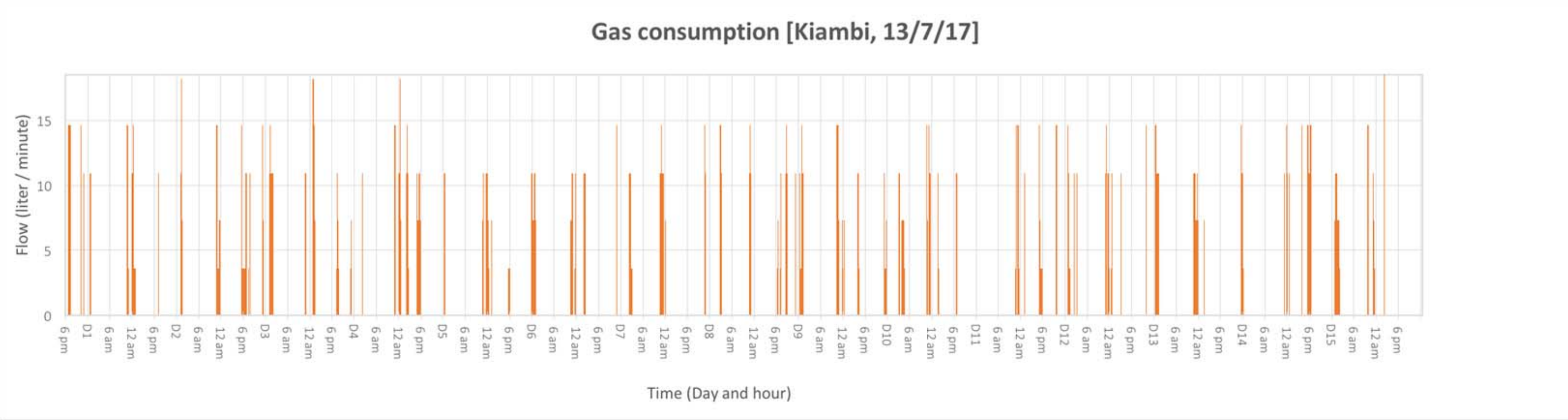

Figure A 34: visualization of flow data of biodigester 6.

8.7.6.3 *Temperature data*

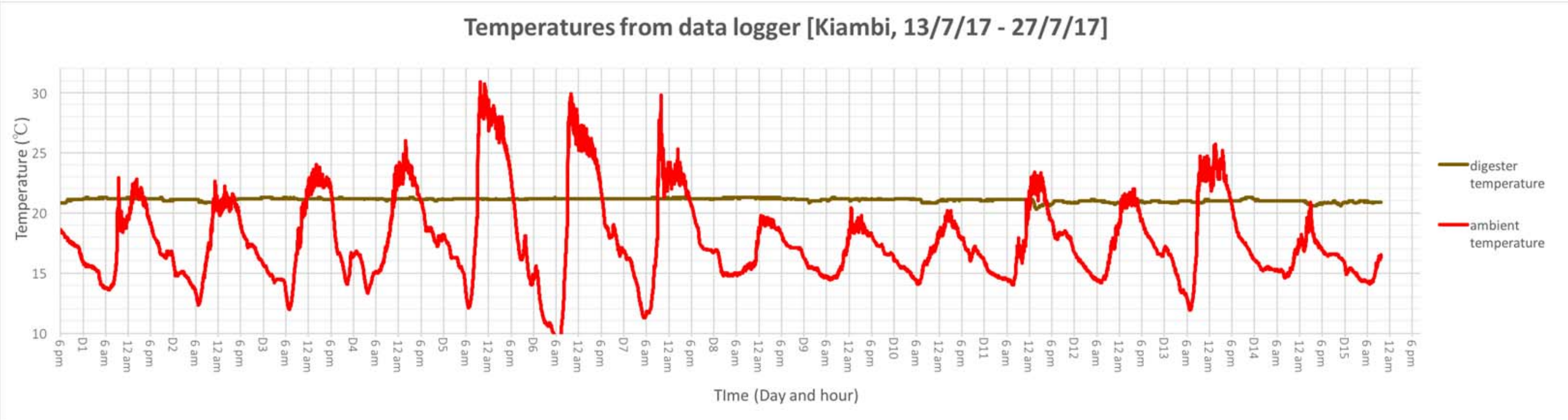

Figure A 35: visualization of slurry and air temperature data of biodigester 6.

8.7.6.4 *Logbook data*

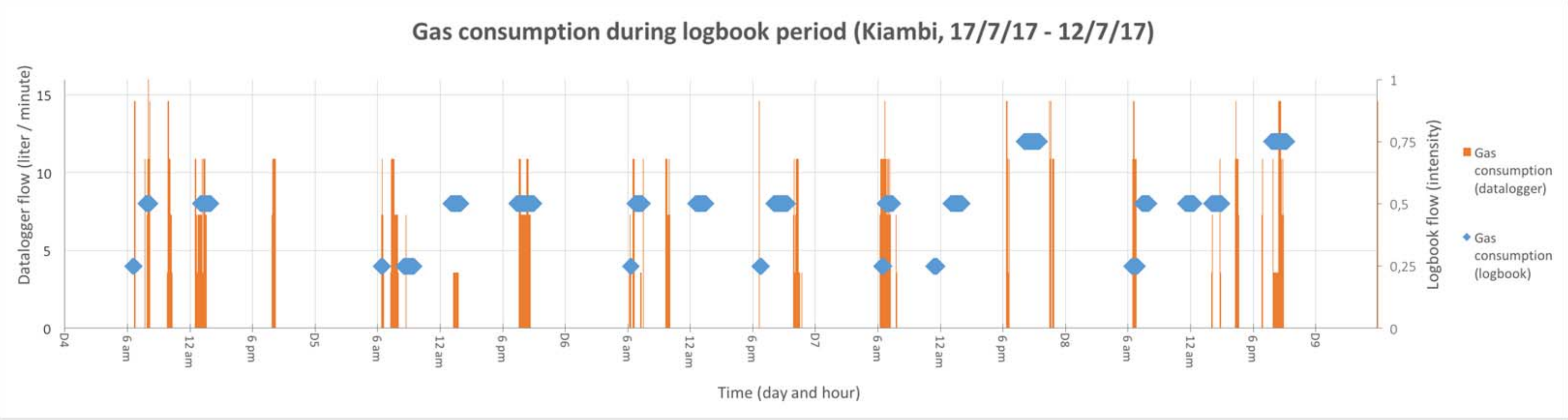

Figure A 36: visualization of flow and logbook data of biodigester 6.

8.7.7 Biodigester 7 (Unkown household, Uganda)

8.7.7.1 *Pressure data*

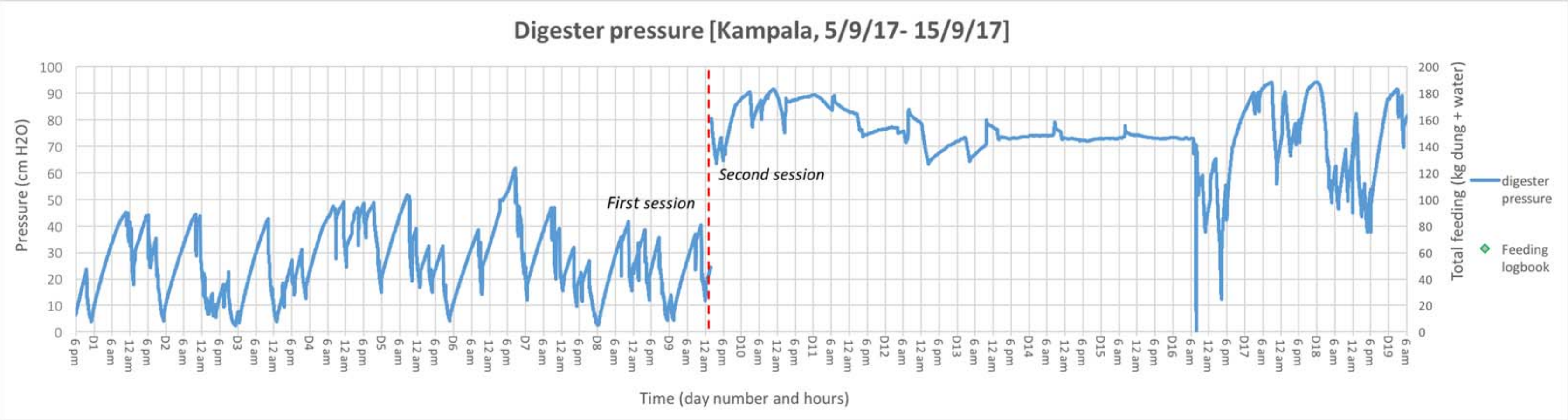

Figure A 37: visualization of digester pressure data of biodigester 7.Note that two sessions were performed, monitoring two different digesters.

8.7.7.2 *Flow data*

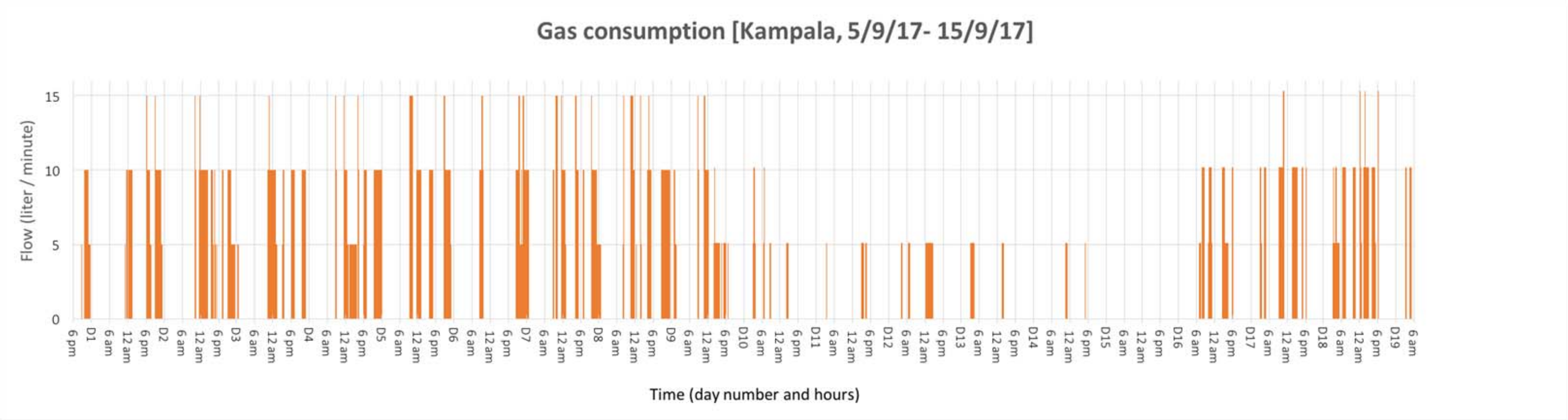

Figure A 38: visualization of flow data of biodigester 7.

8.7.7.3 *Temperature data*

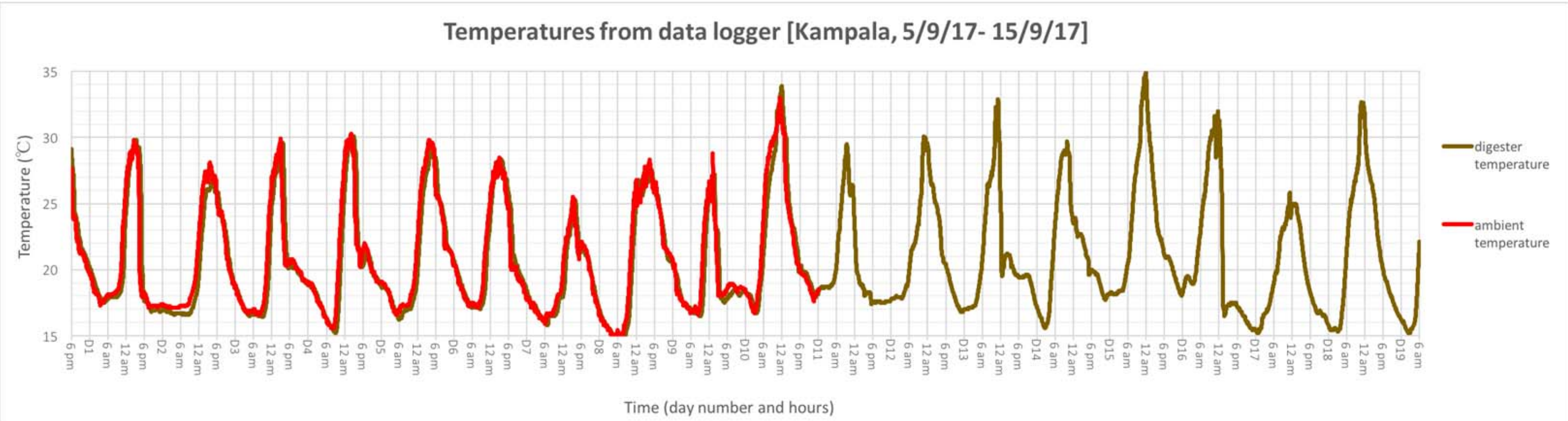

Figure A 39: visualization of slurry and air temperature data of biodigester 7. Note that the ambient temparature sensor broke on day 11.

8.7.8 Biodigester 8 (Michael Mari)

8.7.8.1 *Pressure data*

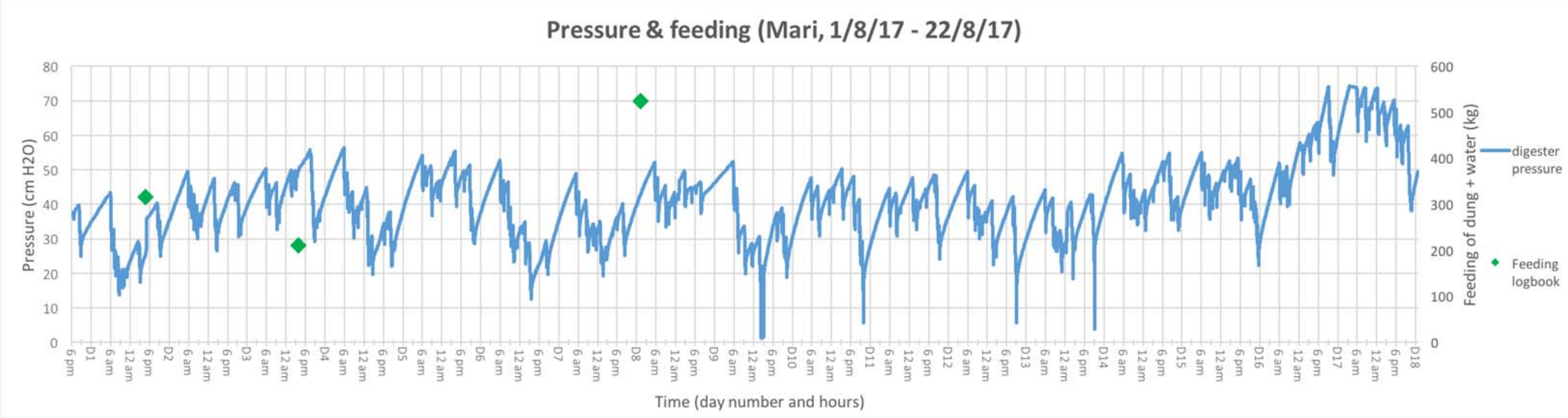

Figure A 40: visualization of digester pressure data of biodigester 8.

8.7.8.2 *Flow data*

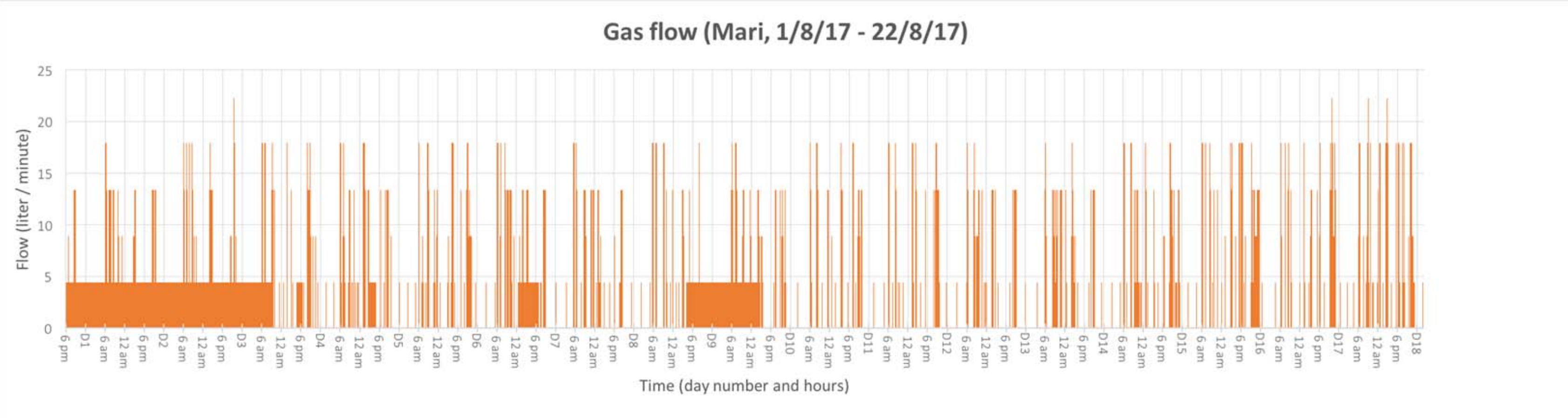

Figure A 41: visualization of flow data of biodigester 8.

8.7.8.3 *Temperature data*

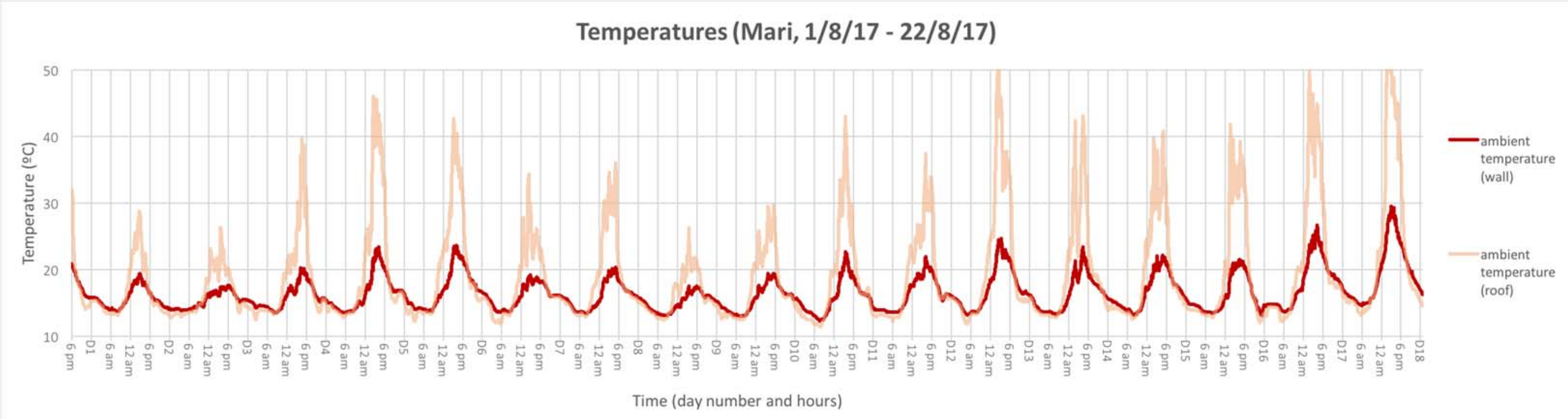

Figure A 42: visualization of slurry and air temperature data of biodigester 8. Note that both temperature sensors were used for monitoring the ambient air temprature in two different ways.

8.7.8.4 *Logbook data*

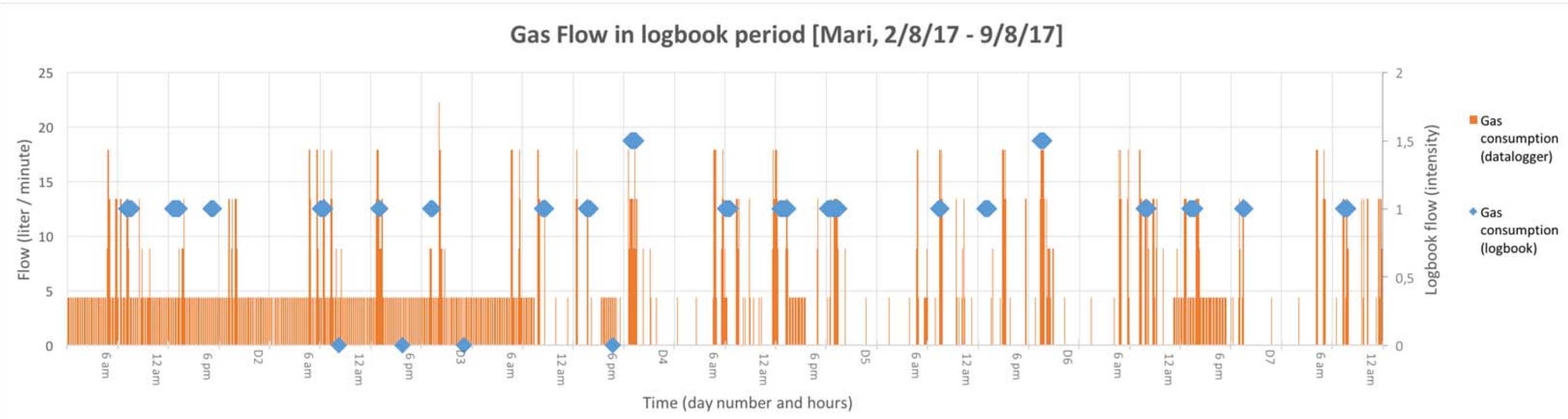

Figure A 43: visualization of flow and logbook data of biodigester 8.

8.7.9 Biodigester 9 (Johnson Kibui)

8.7.9.1 *Pressure data*

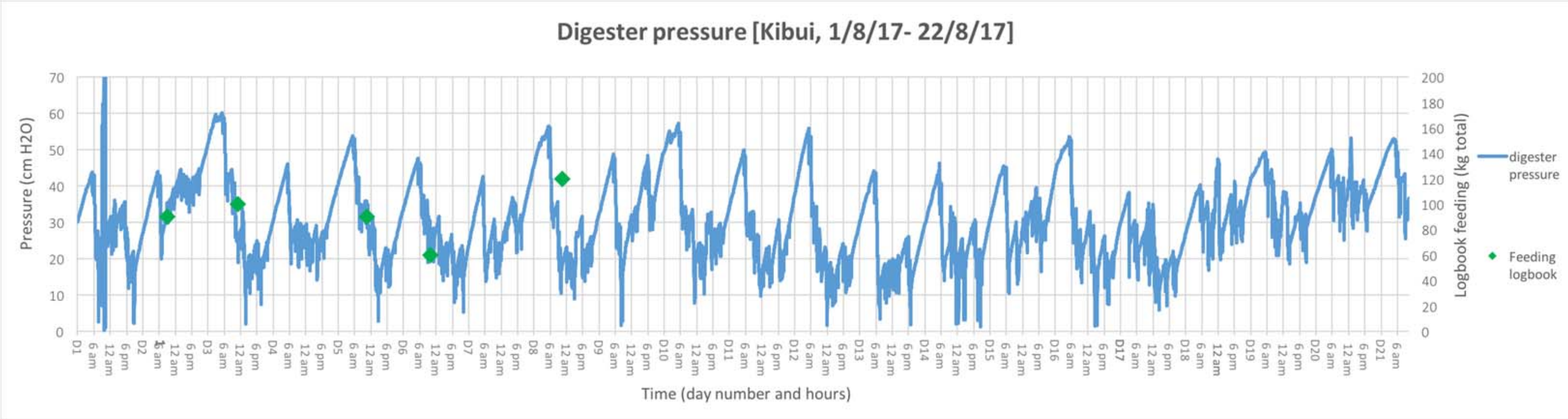

Figure A 44: visualization of digester pressure data of biodigester 9.

8.7.9.2 *Flow data*

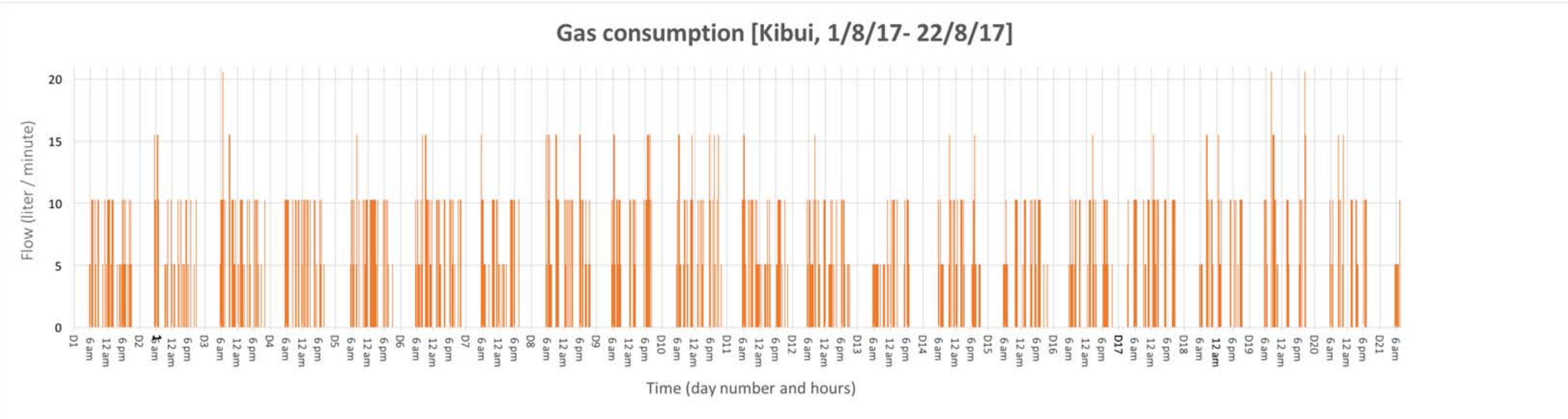

Figure A 45: visualization of flow data of biodigester 9.

8.7.9.3 *Temperature data*

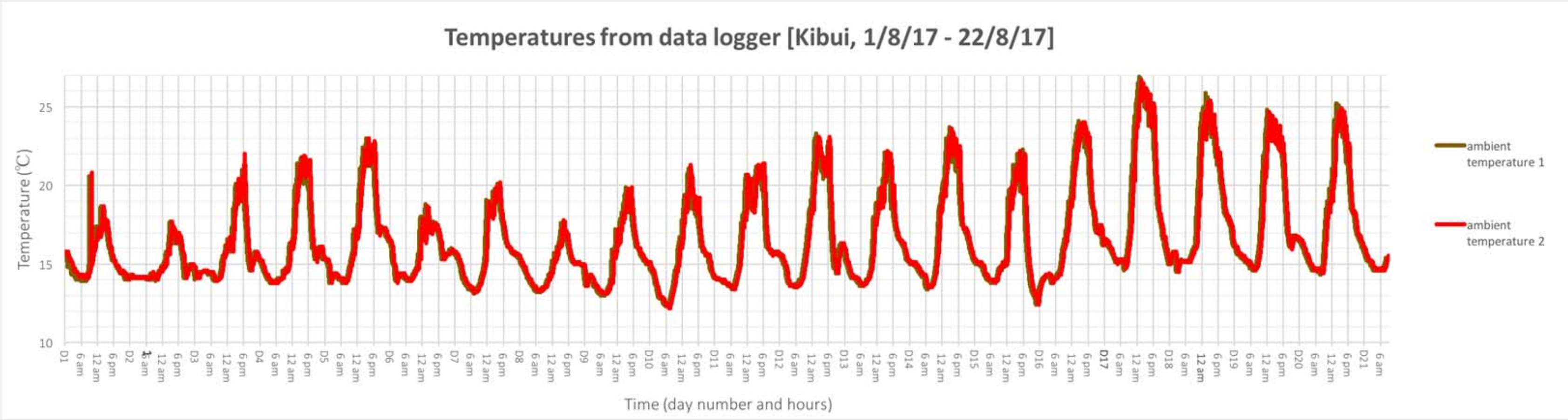

Figure A 46: visualization of slurry and air temperature data of biodigester 9. Note that both sensors were used to measure the ambient air temperature.

8.7.9.4 *Logbook data*

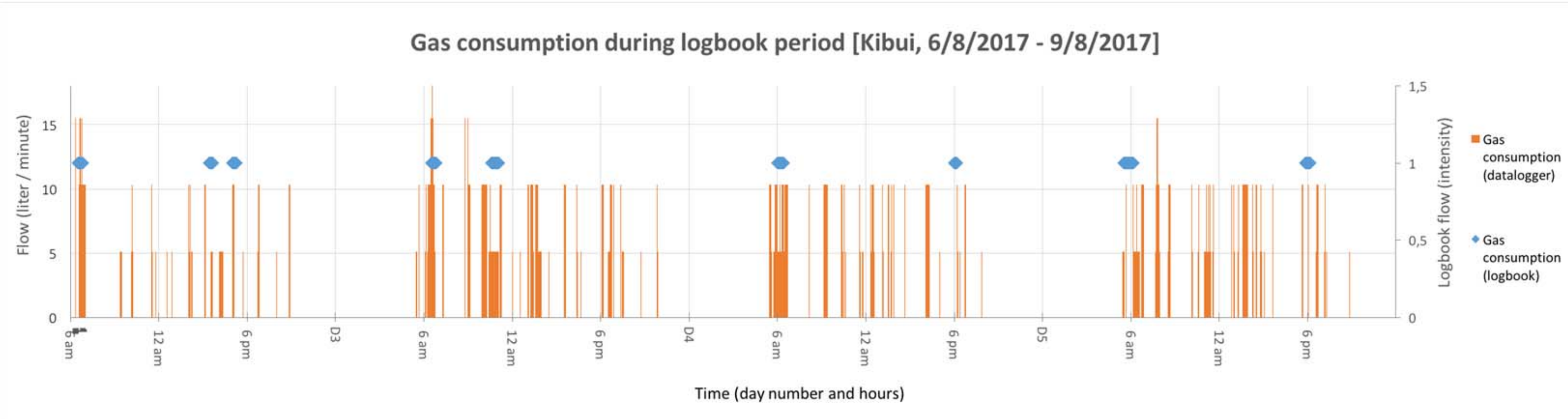

Figure A 47: visualization of flow and logbook data of biodigester 9.

8.7.10 Biodigester 10 (Rehau, covered)

8.7.10.1 *Pressure data*

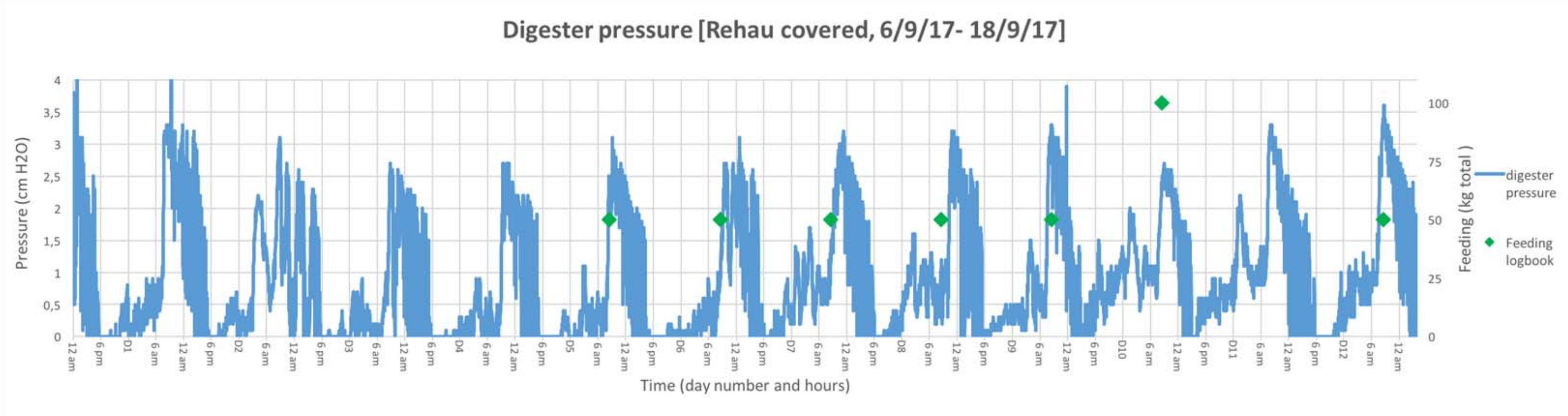

Figure A 48: visualization of digester pressure data of biodigester 10.

8.7.10.2 *Flow data*

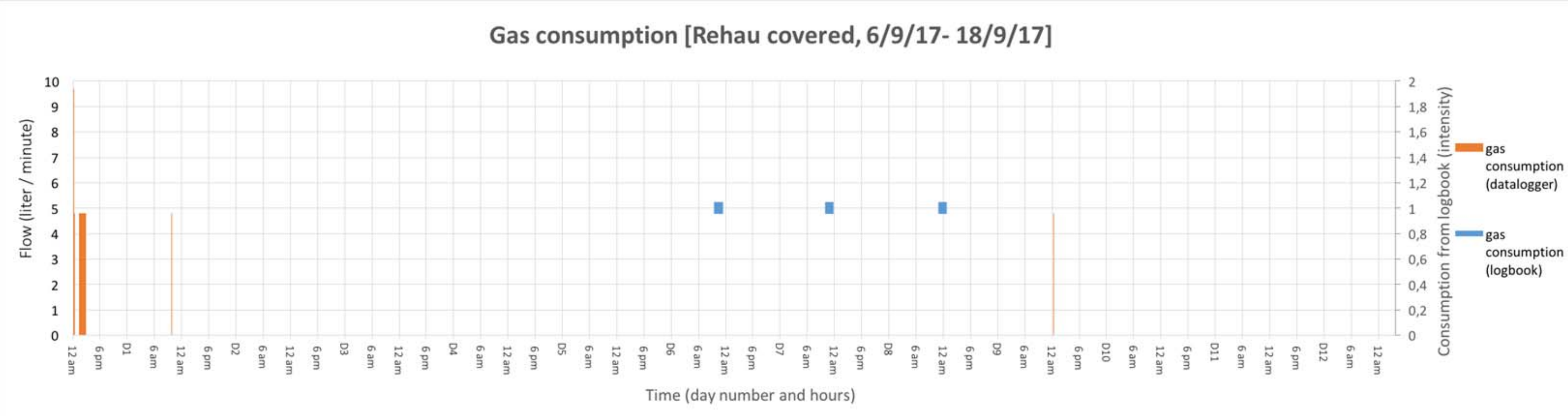

Figure A 49: visualization of flow data of biodigester 10.

8.7.10.3 *Temperature data*

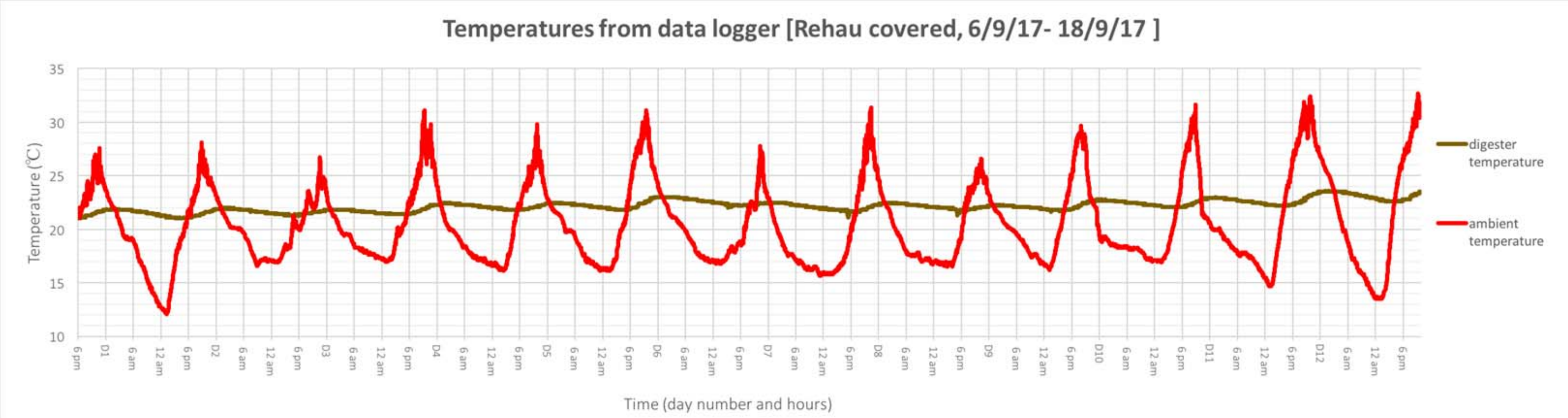

Figure A 50: visualization of slurry and air temperature data of biodigester 10.

8.7.11 Biodigester 11 (Rehau, uncovered)

8.7.11.1 *Pressure data*

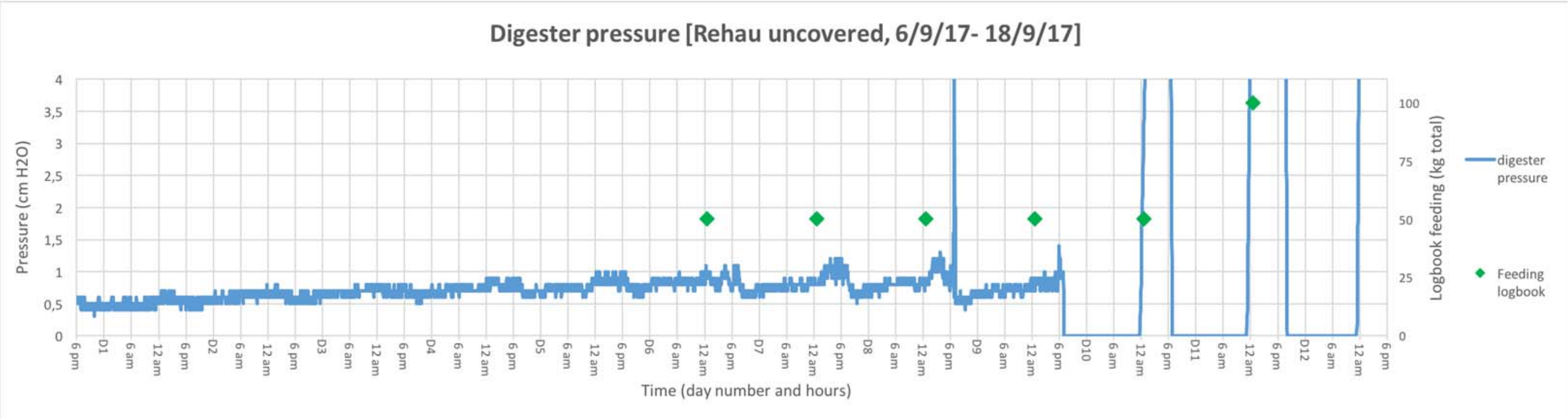

Figure A 51: visualization of digester pressure data of biodigester 11.

8.7.11.2 *Flow data*

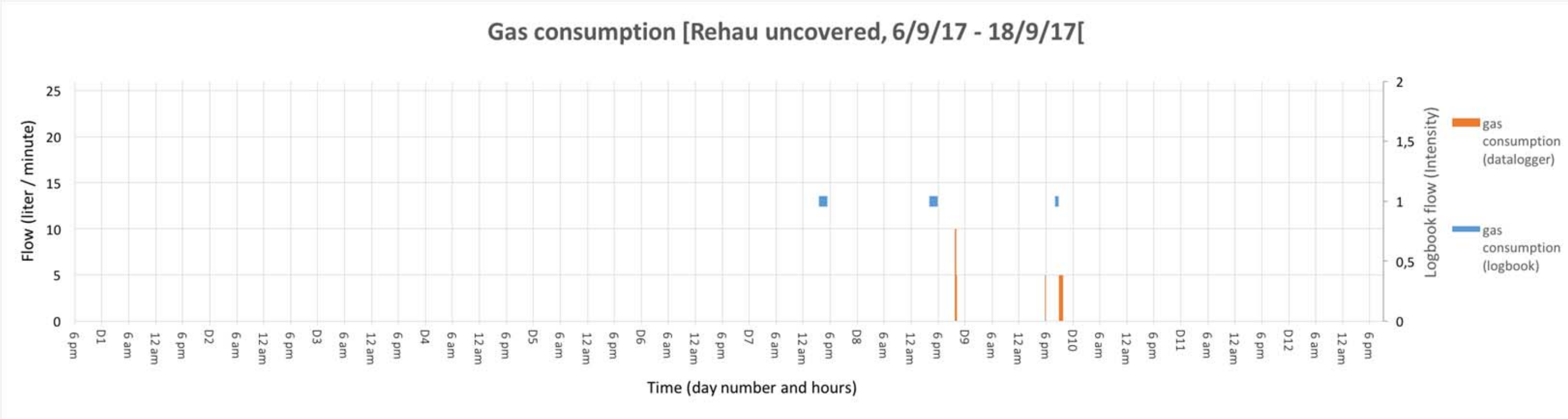

Figure A 52: visualization of flow data of biodigester 11.

8.7.11.3 *Temperature data*

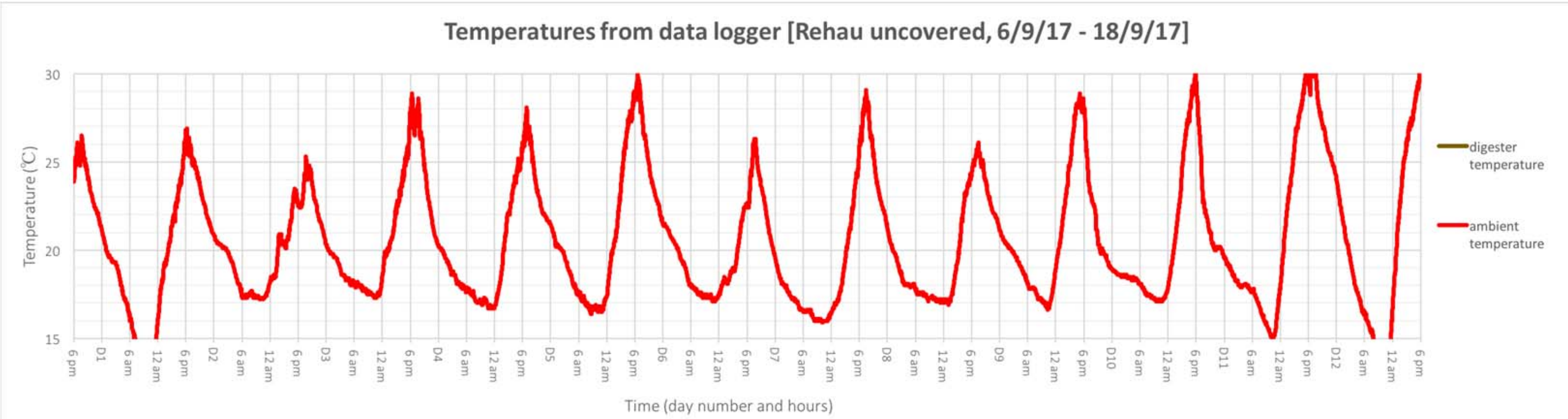

Figure A 53: visualization of slurry and air temperature data of biodigester 11.

8.7.12 Biodigester 12 (Blueflame)

8.7.12.1 *Pressure data*

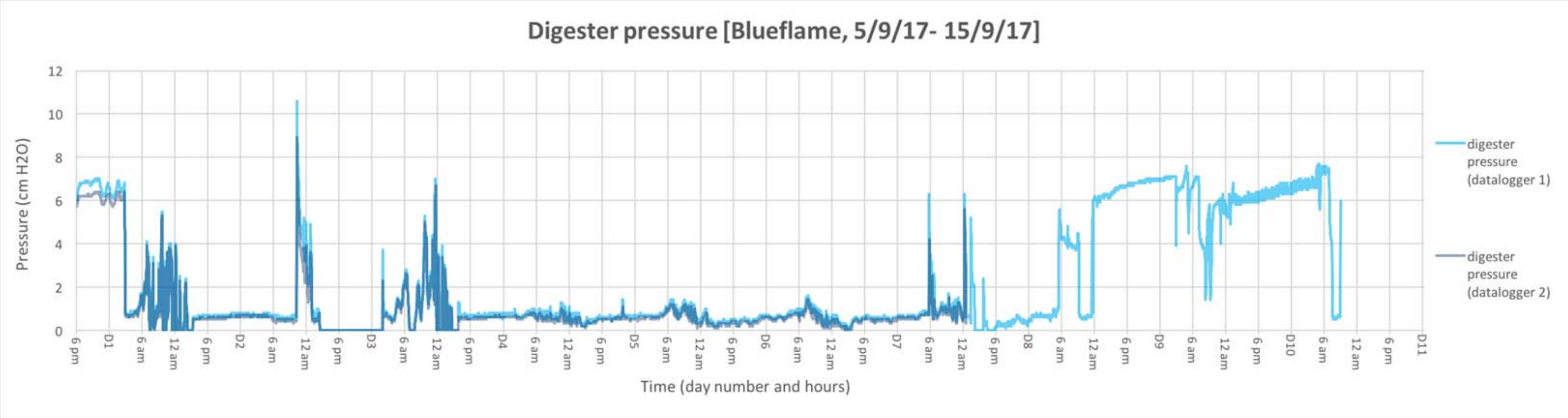

Figure A 54: visualization of digester pressure data of biodigester 12. Note that the main valve was closed during the majority ofperiod from day zero to day 8. Therefore, the pressure during this period is not representative for the pressure in the digester.

8.7.12.2 *Flow data*

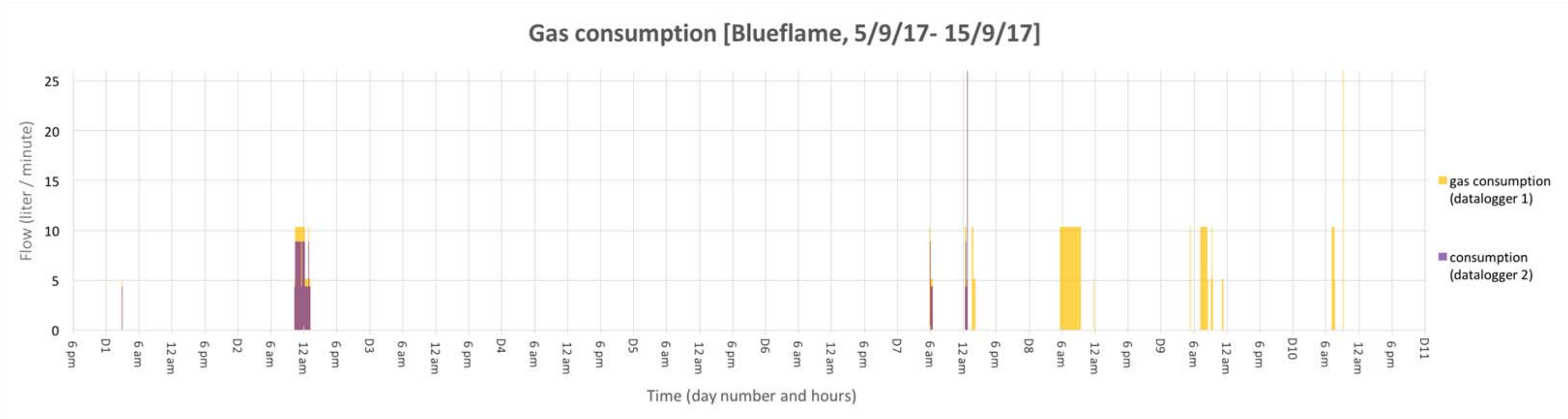

Figure A 55: visualization of flow data of biodigester 12.

8.7.12.3 *Temperature data*

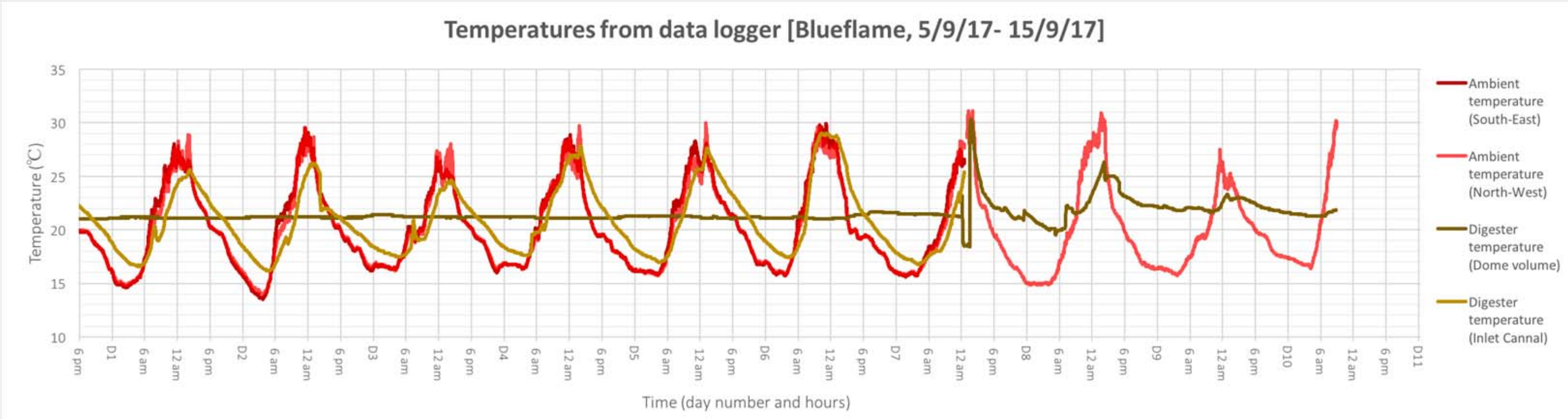

Figure A 56: visualization of slurry and air temperature data of biodigester 12. Note that the data logger mounted at the north-west was removed at day seven. Therefore, the ambient temperature from the north-west side and the digester temperature through the inlet have only be monitored in this period.