# INVESTIGATING A SUSTAINABLE OPERATIONAL METHOD FOR A MICRO-SCALE BIODIGESTER IN SOUTH AFRICA

**MSc (FULL TIME) DISSERTATION**

*Prepared by*

Maphumzane Stanley Semelane

*Submitted to*

A dissertation submitted to the School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

**Supervisor(s): Dr. Diakanua Nkazi**

31 January 2019

# DECLARATION

The dissertation work entitled "Investigating a sustainable operational method for micro-scale biodigester in South Africa" is my own and unaided work, under the guidance of Dr. Diakanua Nkazi. It is being submitted for the Degree of Master of Science in Chemical Engineering to the University of the Witwatersrand, Johannesburg. The work presented in the dissertation is original and not submitted in full or part for any degree or examination in any other body or organization or person outside the University.

..........................................
Signature of Candidate

31 January 2019

# ABSTRACT

The adoption of micro-scale biogas digesters can play a significant role in reducing indoor pollution and promoting socio-economic development. This research aims to investigate a sustainable operational method for a South African micro-scale biodigester. The factors affecting a sustainable operation of a digester, the economic and market model analysis and an assessment of the current South African policy is discussed with an objective to improve the biodigester legislative framework. To operate a sustainable micro-scale biodigester, a compact project management should be established and qualitative data collection that could not be collected during the digester needs analysis community meetings should be gathered from community groups. Gathering data through community groups strengthens project integration into communal structures. Community consultation highlights whether there is an interest or not from the rural communities. The findings indicated that a compulsory maintenance contract guarantees a constant digester feeding thus solidifying microorganism sustenance. A routine maintenance plan ensures that all digester mechanical failures are minimised. The economic and market model analysis showed that micro-scale biodigesters are generally government or donor-funded in South Africa. Lack of financial resources ring-fenced for digester maintenance was identified as the cause for digester failure. The reviewed analysis of an economic and market model recognised the lack of digester regulation, poverty levels in rural regions, and lower affordability rates as a limitation for micro-scale biodigester adoption. The existing South African energy policy analysis indicated gaps for a sustainable micro-scale biodigester operation. Overall, the supplementary environmental and socio-economic benefits associated with a sustainable biodigesters operation add value to the livelihoods of rural dwellers through reducing energy poverty and encouraging economic development in rural communities.

# DEDICATION

I dedicate this work to my mother and my late father whom both contributed significantly to my education. I know you are very proud of me as I complete this milestone. I dedicate this work to the omnipresence of God for granting me strength and opportunity to finish this race. I also dedicate this work to my family members for their support at all times.

# ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Diakanua Nkazi for believing that I can be able to execute this research project. I would not have been able to finish this dissertation without your guidance. I profoundly thank Mr Alistair McMaster who was my line manager while I worked for the Eastern Cape Provincial Government. Thank you for all linkages and the relations you have exposed me to, the exposure you gave me have immensely contributed to this research project. A special gratitude to Professor Mamphweli for familiarising and allowing me to examine micro-scale biodigesters under his leadership. I would like to thank the CSIR Energy centre and my line manager Ntombifuthi Ntuli who allowed me to complete this research project. I really appreciate the guidance that you have imparted in this research. Thank you for the support you have provided.

**My support structure**

Thank you to my lovely wife for always supporting me. Your understanding is sincerely appreciated from the bottom of my heart. Thank you for your understanding and prioritising other obligations when I could not make it due to time this research required. Thank for helping me with this project, I really appreciate all you have done.

## TABLE OF CONTENTS

**LIST OF FIGURES**

## LIST OF TABLES

## LIST OF ABBREVIATION

| | |
|---|---|
| AD | Anaerobic Digestion |
| AFPRO | Action for Food Production |
| BOD | Biochemical Oxygen Demand |
| CAMARTEC | Centre for Agricultural Mechanization and Rural Technology |
| COD | Chemical Oxygen Demand |
| CSP | Concentrated Solar Power |
| CSTR | Completely mixed digester |
| DfID | Department for International Development |
| DM | Dry Matter |
| DME | Department of Minerals and Energy |
| DoE | Department of Energy |
| EIS | Environmental Sustainability Index |
| ELR | Environmental Loading Ratio |
| GHG | Greenhouse Gas |
| GIZ | The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH |
| HRT | Hydraulic Retention Time |
| IBBK | International Biogas and Bioenergy Centre of Competence |
| INEP | Integrated National Electrification Program |
| IRENA | International Renewable Energy Agency |
| KVIC | Khadi and Village Industries Commission |
| MPF | Mixed plug flow digester |
| MW | Megawatt |
| NCF | Net Cash Flow |
| NERSA | National Energy Regulator of South Africa |
| NPV | Net Present Value |
| OLR | Organic Loading Rate |
| PBDs | Prefabricated Biogas Digesters |
| PBP | Pay Back Period |
| PFR | Plug Flow Reactor |
| PV | Photovoltaic |
| PW | Present Worth |
| REI4P | Renewable Energy Independent Power Producers |
| SABIA | South African Biogas Industry Association |
| SANEDI | South African National Energy Development Institute |
| SE4ALL | Sustainable Energy for All |
| SRT | Solids Retention Time |
| TOC | Total Organic Carbon |

| | |
|---|---|
| TW | Terawatt |
| UASB | Up-flow anaerobic sludge blanket |
| UBPL | Upper-bound Poverty Line |
| VFA | Volatile Fatty Acids |
| WWTP | Wastewater Treatment Plants |

## LIST OF NOMENCLATURE

| | |
|---|---|
| $ | Dollar currency |
| $CH_4$ | Methane Gas |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon dioxide |
| $H_2$ | Hydrogen |
| $H_2O$ | Water Vapour |
| $H_2S$ | Hydrogen Sulphide |
| $m^3$ | Cubic Meter |
| $N_2$ | Nitrogen |
| $NH_3$ | Ammonia |
| $O_2$ | Oxygen |
| $T_c$ | Cost of economic benefits for a household |
| $T_s$ | Cost of environmental benefits for a household |

## PUBLICATION AND CONFERENCE (AVAILABLE IN APPENDIX: J & K)

Peer reviewed Paper: A sustainable operational method for micro-scale biodigesters in South Africa. *The International Journal of Multi-Disciplinary Research.* Aug 2018.

Conference presentation: A proposed sustainable operational method for micro-scale biodigesters in South Africa. *International Multi-Disciplinary Conference*, Lusaka, Zambia, 29-31 Aug 2018.

# CHAPTER 1

# 1. INTRODUCTION

## 1.1 Background and justification

The South African causes for biodigester failure need to be understood since they have an impact in the lifespan of a digester. The factors that contribute to a short lifespan for a biodigester will continue to hinder a successful adoption of micro-scale digesters as well as encouraging investments. Energy is an essential element for stimulating economic growth, social development, human welfare and improving the standards of living (Vijay *et al*., 2015). Over the years, dependence on fossil fuels has increased significantly, however, concerns about greenhouse gas (GHG) emissions have also increased, prompting an increase in adoption of renewables and other cleaner sources of energy (Vijay et al., 2015). Biomass can play a vital role in the transition to a low carbon economy, especially in turning waste to biogas (Vijay et al., 2015). Current world energy consumption is roughly about 15 terawatts (TW) per annum. However, renewable energy only accounts for about 7.8% of the total global energy consumption (Roopnarain & Adeleke, 2017). Energy demand from Sub-Saharan Africa is approximately 4% of the global energy annual consumption (Roopnarain & Adeleke, 2017). The 4% energy consumption indicates that there is still an electrification backlog within sub-Saharan Africa population that is estimated to be about 13% of global inhabitants (Roopnarain & Adeleke, 2017).

The research seeks to develop a sustainable method for operating micro-scale biogas digesters in South Africa. The adoption of biogas digesters can play a significant role in reducing energy poverty, reduce indoor pollution and promote socio-economic development. South Africa has a substantial renewable energy resource, with an outstanding solar and wind perspective when compared with other regions internationally (DoE, 2015). South Africa is also endowed with other renewable energy sources in the area of bio-energy and small-scale hydropower (DoE, 2015). Renewable energy in South Africa has developed into a significant industry, with approximately R189.10 billion worth of investments in the area of solar photovoltaic (PV), Concentrated Solar Power (CSP) and wind power plants (DoE, 2015). This shows that there is an insignificant investment in the biogas technology hence Solar PV, CSP and wind accounts for 98% of the Renewable Energy projects developed in South Africa. The evaluation of renewable energy cost indicates that biogas investment cost requires not as much as other renewables such as coal, wind and solar (Rao *et al*., 2010).

**Table 1: South African renewable energy investment**

***Source: (DoE, 2015).***

| | Wind | Solar PV | CSP | Biomass | Small hydro | Landfill gas |
|---|---|---|---|---|---|---|
| R billion invested | 73.4 | 62.4 | 53.3 | 2.3 | 1.0 | 0.3 |
| Percentage share of investment | 38% | 32% | 28% | 1% | 1% | 0% |
| Capacity (MW) | 3 357 | 2 292 | 600 | 42 | 19 | 18 |

Table 1 indicates a total investment of R190 billion in Solar PV, CSP and wind. This is through the Renewable Energy Independent Power Producers Procurement Program (REI4P) initiative (DoE, 2015). Comparatively, the biogas technology is lagging behind, with roughly less than 1% investment in the REI4P program (DoE, 2015). Since 1994 the electrification of households in South Africa has been remarkable, however, many of rural and poor household is still dependent on traditional fuels such as paraffin and wood for their basic energy needs (Lloyd, 2014). The basic energy needs of most households include cooking and heating (Lloyd, 2014). For the well-off households, luxury and convenience are important, however, poor households and those located in deep rural areas choose their energy needs mainly based on cost (Lloyd, 2014). Fuelwood as a source of energy is not regulated in South Africa hence it is directly consumed by poor households (Davidson et al., 2006). South Africa utilises 45% of the total energy produced in Africa (Karekezi & Kihyoma, 2013). Most of this energy is produced by the South African national energy utility, Eskom, which generates over 85% of South African electricity from coal inhabitants (Roopnarain & Adeleke, 2017). The protuberant utilisation of coal-generated electricity in South Africa has resulted in South Africa being the forefront GHG emitter in Africa inhabitants (Roopnarain & Adeleke, 2017). Biogas adoption reduces carbon emissions and this in line with the Kyoto protocol that South Africa ratified in 2002 under the United Nations Framework Convention on Climate Change (DME, 2003).

Given the latter, it is necessary to understand the reasons for the under-development of a potentially important energy sub-sector in the framework of micro-scale biodigesters at the household level. Currently, South Africa does not have a biogas strategy or a policy that will envisage an effective adoption of micro-scale biogas digesters. The safety standards for micro-scale biodigesters have not been formulated, including guidelines on how to successfully operate micro-scale biogas digesters. The possibilities for an effective operational procedure for micro-scale biodigesters in South Africa need to be understood. The barrier, benefits and support mechanisms for the sustainable realisation of micro-scale biogas digester is fundamental in ensuring a flourishing acceptance of this technology. Predominantly in poor communities where a substantial number of households are still not connected to the national grid. This will significantly contribute to the development bio-energy sector and create an energy mix at the household level.

South Africa has a reasonable amount of rural dwellers that rely on wood for cooking purposes (Lloyd, 2014). The utilisation of wood for meeting energy needs is roughly about 52.5% in Limpopo, 24% in Eastern Cape, 19% in Mpumalanga and KwaZulu Natal (Lloyd, 2014). The development of a sustainable method for effectively operating micro-scale biodigesters in South Africa will have a direct positive impact on the bio-energy industry and further, encourage the development of the legislative framework for micro-scale biodigester for the benefit of the entire biogas industry. Biogas application for the purposes of electricity generation and biomethane or compressed natural gas has been excluded from this research. However, benefits that are a result of micro-scale biodigester have been widely covered. Furthermore, this research distinguishes micro-scale biodigester from an industrial biogas digester. However, the benefits of biogas technology are covered extensively within the micro-scale biodigester framework.

## 1.2 Problem statement

A failing biogas project, regardless of the size, has unfavourable consequences on the general perceptions and adoption of micro-scale biogas technology. A significant number of digesters have failed in South Africa hence the initiative to investigate a sustainable operational method for micro-scale biodigester in South Africa comes as a direct response that seeks to understand the fundamental limitations for the successful implementation of micro-scale biodigesters in South Africa. Biogas plants whether small, medium or large scale offer three critical advantages for the waste management problem (GIZ, 2015). Firstly, it contributes to dealing with potentially complex waste streams in an adequate and concrete manner. Secondly, it displaces methane gas that could have been atmospheric in the absence of biogas project implementation. Finally, it offers an organic-rich by-product in a form of fertilizer. For many years, the biogas technology has been deployed as a solution to waste management in Europe and countries like Germany that are currently leading with digester installations (IBBK, 2014).

Given that the micro-scale biogas technology is reasonably new in South Africa and still lacking the necessary legislative framework that will integrate it to existing waste management policies. It is important to develop a sustainable operational method for biodigesters that will ensure the causes for failure are minimised while the lifespan is improved.

Figure 1 indicates one of the fundamental environmental problems is waste management; this is instigated by high volumes of waste streams generated on daily basis (Al Seadi *et al*., 2010). This challenge has compelled a number of countries to come up with waste management strategies and policies in order to curb this through various activities such as climate change politics, mitigating against global warming and trying to manage uncontrollable waste streams that landfill sites struggle to deal with effectively (Al Seadi *et al*., 2010). Micro-scale biogas digesters can play a role in alleviating energy poverty, particularly in areas where some communities are still burning firewood for basic energy needs (Colombo *et al*., 2013). In terms of sustainable development and Sustainable Energy For All (SE4ALL), micro-scale biodigesters are a mature technology and appropriate for alleviating energy poverty for the "energy poor" while they address the waste management problem (Colombo *et al*., 2013). However, micro-scale biodigesters have not matured in South Africa when it is compared to other countries. Manyi-Loh *et al*. (2013) indicate that biodigesters mitigate a wide range of environmentally unfriendly gases, enhances sanitation, and reduces water and atmospheric pollution. Mukumba *et al*. (2016a) further enlighten that the anaerobic digestion process produces minimal GHG compared to wastewater treatment methods like landfilling and compositing.

**Figure 1: Uncontrollable waste streams**
***Source: Al Seadi et al., (2010).***

The research questions are intended to determine how micro-scale biodigesters can be operated in a sustainable approach. This is to encourage the development of micro-scale biodigesters policy framework, safety standards, operations and maintenance plan suitable for South Africa.

- Why are micro-scale biodigesters not operated in a sustainable approach in South Africa?
- What mechanism can be implemented to promote a sustainable micro-scale biodigester operational model for the energy poor?
- Why South Africa does not have a micro-scale biogas digester strategy?
- What can be done to increase the lifespan of micro-scale digesters in South Africa?
- Why are micro-scale digesters not regulated in South Africa?

## 1.3 Research objectives

The aim of this research is to investigate a sustainable operating method for South African micro-scale bio-digester. To meet the aim of this project, the following objectives will be discussed:

- To investigate the biogas production process for cooking purpose in order to understand the cause of short lifespan and failures of locally produced micro-scale bio-digester;
- To investigate the causes for failure in the implementation of micro-scale biodigesters in South Africa;
- To investigate a sustainable operational and maintenance plan for micro-scale biodigesters in South Africa;
- To investigate a local market model of micro-scale bio-digester;
- To investigate sustainable policy framework for a successful implementation of micro-scale biodigester in South Africa.

## 1.4 Research Approach and research outline

Micro-scale biodigesters have failed the sustainability test in South African for a number of reasons. Most installed micro-scale digester are donor aid funded, this normally does not cater for maintenance and operation thus leading to a high failure rate that is not related to the actual biogas technology. A sustainable operational method for micro-scale biodigester needs to be developed as a sustainable solution that will limit digester malfunctioning. The schematic diagram of the research approach is shown in Figure 2.

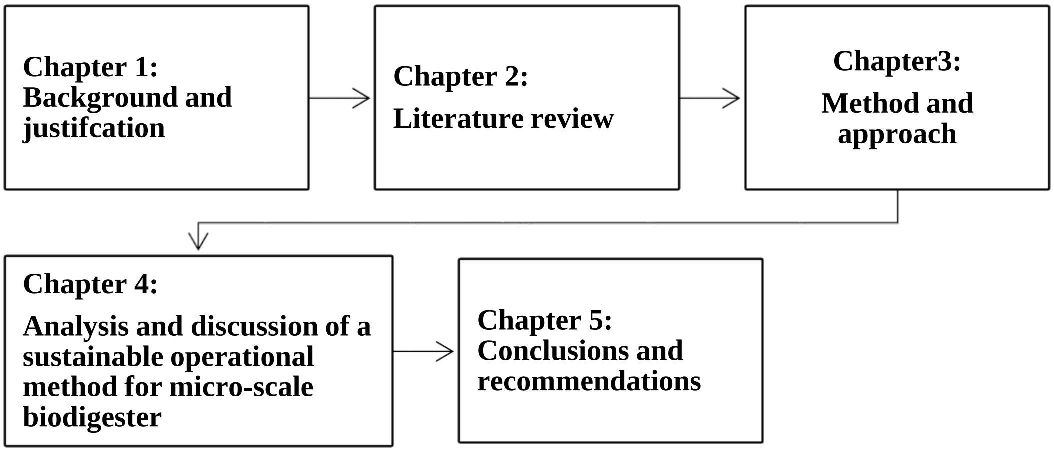



**Figure 2: A Graphic research approach**

**Chapter 1:** This chapter provides a brief introduction, causes for digester failure and problems relating to the successful implementation biodigesters. Furthermore, research objectives and questions of the study are introduced.

**Chapter 2:** This chapter briefly describes the anaerobic digestion process and the different types of biodigesters. The significant parameters for operating a biodigester successfully is introduced through a digester configuration and gas yield from various feedstock. Environmental and socio-economic benefits of adopting biodigesters is briefly highlighted as well as the role that biogas can play in alleviating energy poverty.

**Chapter 3:** This chapter provides the process and approach followed for developing a sustainable operational method for operating biodigesters in South Africa. The methodology adopted in this study is briefly introduced.

**Chapter 4:** This chapter provides lifespan analysis of a biodigester and causes for digester failure. Parameters that are critical for making biodigesters successful are discussed. A project development process and a sustainable operational method for micro-scale digester is developed. The economic and market model for operating digesters successfully is introduced as well as the required policy framework for South Africa.

**Chapter 5:** This chapter provides the research conclusions and recommendations that can further strengthen a successful implementation of micro-scale biodigesters in South Africa.

# CHAPTER 2

# 2. LITERATURE REVIEW

## 2.1 Micro-scale biodigester process

According to Metcalf & Eddy (1979) the production and collection of biogas from a biological process were firstly chronicled for the first time in the United Kingdom in 1895. Since then, biogas production has developed over the years and continues to advance. Biogas technology is now applied in wastewater treatments plants globally. The energy crisis in the early 1970s ignited awareness on renewable energy including the biogas technology through the Anaerobic Digestion (AD) process (Metcalf & Eddy, 1979).

Today the interest in biogas remains important, the global efforts aimed at displacing fossil fuels used for energy production and the necessity for finding environmentally sustainable solutions representing waste treatment and recycling of animal manure and other organic material (Metcalf & Eddy, 1979). Anaerobic decay starts in the internal digestive territory before it is released as manure loads. The manure loads amalgamate as a foul-smelling organic matter that is inadequately fragmented, this is instigated by anaerobic bacteria exposed to different environmental conditions (Manyi-Loh *et al*., 2013).

The organic decomposition process commences when the biogas feedstock is exposed to sunlight and oxygen; however, organic matter can decompose without exposure to oxygen through an anaerobic fermentation process, in the absence of oxygen the bacteria contained in the matter produces gas. A biogas system is a huge tank or digester through which anaerobic digestion originates inside the tank to produce methane gas. For biogas system to continuously produce methane gas, the operator needs to feed the digester households products like kitchen waste, manure from livestock and market waste. The methane gas produced inside the biogas system must be utilised for cooking, lighting and other energy requirements. Biogas is regarded rich as an energy source and appropriate in many ways, although it is much easier to use biogas for heating purposes. (Bagher *et al*., 2015).

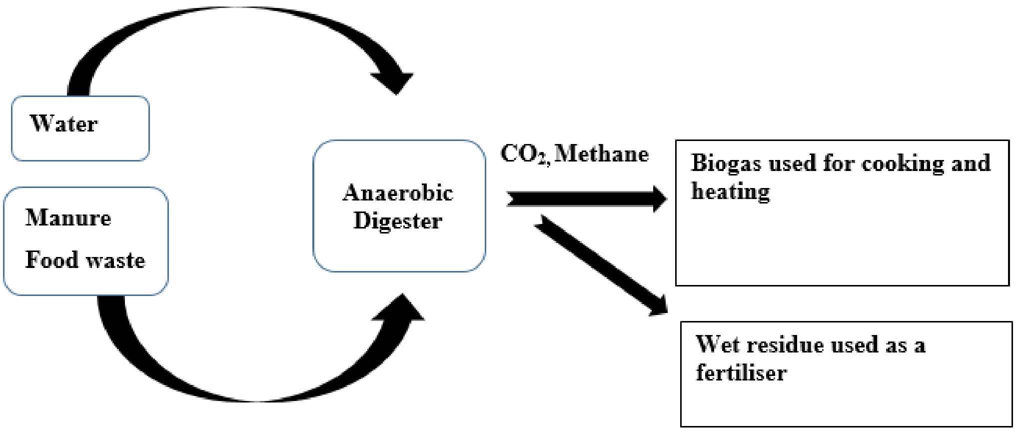



**Figure 3: Micro-scale Anaerobic Digestion Process**

***Source: Adapted from Haig & Gorgens (2013).***

Figure 3 indicates the biogas generation cycle that Al Seadi *et al*. (2010) explains as a combustible gas that contains mainly methane and carbon dioxide. Other gases present in biogas are insignificant. The digestate as a decomposed substrate that is rich in macro and micronutrients and the two main products are a result of anaerobic digestion which is suitable for energy generation and agricultural cultivation (Al Seadi *et al*., 2010). Biogas produces primarily 25-75% methane, 30-40% carbon dioxide and other immaterial traces of gases such as carbon monoxide, ammonia, water vapour, hydrogen sulphide, nitrogen and hydrogen as indicated in Table 2.

**Table 2: Gases contained in biogas**

***Source: (Colombo et al., 2013; Al Seadi et al., 2008).***

| **Biogas Composition** | **Chemical formula** | **Percentages (%)** |
|---|---|---|
| Methane | $CH_4$ | 25 – 75 |
| Carbon dioxide | $CO_2$ | 30 – 40 |
| Hydrogen sulphide | $H_2S$ | 0.1 – 0.5 |
| Water vapour | $H_2O$ | 1 – 2 |
| Nitrogen | $N_2$ | 1 – 2 |
| Ammonia | $NH_3$ | 0.1 – 0.5 |
| Carbon monoxide | CO | 0 – 0.5 |
| Oxygen | $O_2$ | 0 – 0.5 |
| Hydrogen | $H_2$ | 0 – 0.5 |

Methane gas shown in Table 2 is a significant element in biogas due to its capability of being combustible. Biogas can be directly employed for thermal applications or for power generation, moreover, biogas can be enhanced to "biomethane" which is defined as methane produced from upgrading biogas with properties close to natural gas, thus making it an interesting fuel to support the transition from fossil fuels to renewables (Colombo *et al*., 2013; Al Seadi *et al*., 2008).

## 2.2 Biogas production through an AD

Biogas production through an AD from organic waste, manure and slurries converts into renewable energy and offers a digestate as by-product fertiliser that can be utilised for agricultural cultivation purposes. Through this process, the organic fraction is removed from general waste streams thus increasing the efficiency of energy conversion. This creates biochemical stability of the waste generated. AD is a microbiological process of the decomposition of organic matter in the absence of oxygen, common to many natural environments. It is largely applied today to produce biogas in airproof reactor tanks or underground containers that ensures that oxygen is excluded from the bacteriological decomposition process that converts to biogas over time (Al Seadi *et al*., 2008).

According to Luo *et al* (2016) an AD is a sustainable mechanism for treating various forms of waste and it reduces GHGs. Biogas is a very efficient energy source especially in rural areas and emerging economies. The utilisation of household biogas digesters has been very minimal due to various reasons like shortages of feedstock and poor biogas production rates. There is an important need for good quality micro-scale household biogas digesters designs that can assist in improving the household biogas utilisations uptake rate.

## 2.3 Common biodigester designs in South Africa

Van Hessen (2014) states that domestic micro-scale biodigesters are less complex to manage. They convert both human and animal waste in small quantities into valuable biogas (Van Hessen, 2014). DfID (2011) states that the three main types of digesters available for use in Sub-Saharan Africa are floating drum, fixed dome and balloon plastic digester. Globally, biogas technology has largely promoted fixed dome digesters, with approximately 38 million already installed in China and 6 million installations planned per year (DfID, 2011). In addition to this, India has initiated a programme to upgrade all their current floating drum biogas digesters to fixed dome design (DfID, 2011; Colombo *et al*., 2013). By 2006 there were approximately 16 million micro-scale biogas digesters installed worldwide and the numbers have been increasing from that time (Brown, 2006). Micro-scale biodigesters are categorized through various models, these are quadrilateral, globular, ground and underground designs (Mulinda *et al*., 2013). Mulinda *et al*. (2013) describe an operative concept for diverse micro-scale biodigester designs to be dependent on digester size which regulates gas yields, investment cost and digester monitoring overhead. Mulinda *et al*. (2013) explain that effective utilisation of this concept determines whether a digester fails or succeed. Generated energy from biogas digesters bridges the energy needs of individual families. Van Hessen (2014) explains that biodigester size at household level ranges between 2 and 10 $m^3$ and yields roughly 0.5 $m^3$ biogas per $m^3$ biodigester size. However, the digester sizes differ in some countries, Pakistan and Vietnam build household biodigester up to a maximum of 50 $m^3$ (Ghimire, 2013).

### 2.4 The fixed-dome biodigester plant designs

According to Mulinda *et al*. (2013), the Chinese fixed dome design was established through research that was conducted in mid-1970s, the fixed dome involves a cylindrical digester, rotund on upper and flat or bent on the lowermost part. This was standardised in 2002 to form the GB/T4750-2002 illustrated in Figure 4.

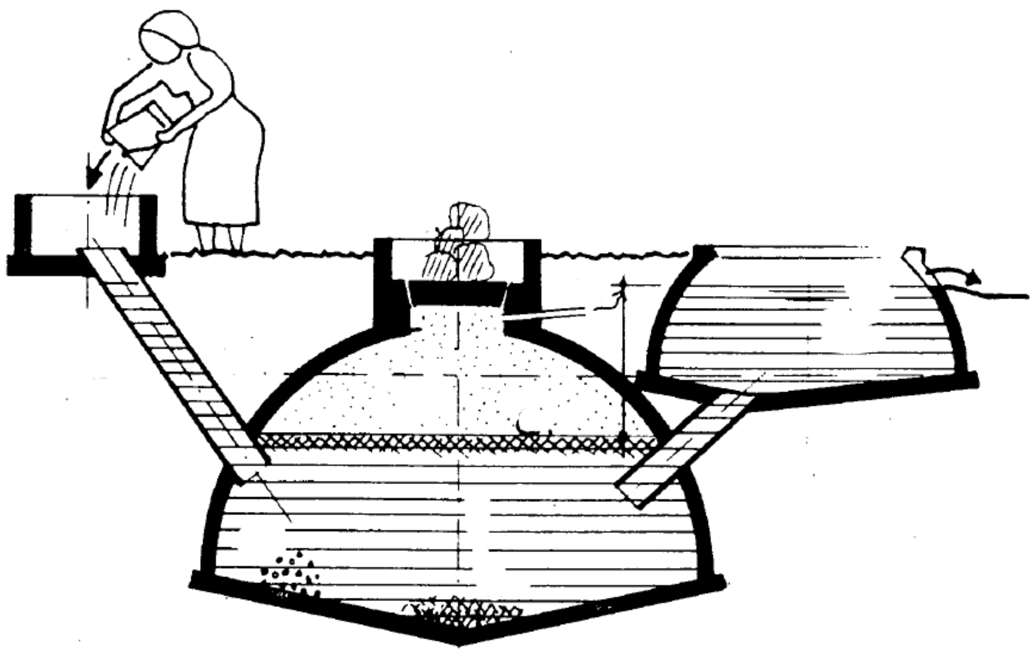


**Figure 4: Fixed dome biodigester plant**

***Source: Thom (1994).***

The fixed dome biodigester plant illustrated in Figure 4 utilises various forms of biomass feedstock which is mixed with water in the mixing tank to form a slurry. The slurry is then fed into the digester through the inlet compartment. Once the digester is moderately filled with the slurry, the feeding of the slurry is stopped for approximately two months to allow the formation of bacteria inside the slurry. After this process (after two months), an anaerobic bacterium created in the slurry decomposes in existing water, subsequently, biogas is generated. After sufficient biogas is generated, the pressure exerted by the biogas drives the expanded slurry into the outlet chamber and it will then run-off into the displacement or overflow tank (Singh, 2010). The spent slurry is manually removed from the displacement tank and used as a fertiliser in the agricultural sector. Singh (2010) explains that the gas outlet above this system is opened when the supply of biogas is required. To ensure that gas production is continuous, the bacterium should always be present, continuous feeding of this system is thus recommended. This system is easily constructed, inexpensive and uses the locally available material for construction (Singh, 2010). According to Rajendran *et al*. (2012) fixed dome models established in India contain the *janta* and *deenbandhu* models. The janta model was first introduced in 1978 where an inlet and outlet of this digester were retained above the dome with the gas pipe fitted on the apex of the dome. The shortcomings of the *janta* model consist of short mixing path of the slurry, discharge of undigested slurry at the top and a lesser amount of gas volumes are generated due to the raised gas pressure (Rajendran *et al*. 2012). Action for Food Production (AFPRO) launched an adapted *janta* model known as *the deenbandhu* model in 1984. This model comprises two spheres of different diameters. The lower sphere is responsible for the fermentation process, while the upper one is used for storage purposes (Rajendran *et al*. 2012).

### 2.5 Modified fixed dome designs

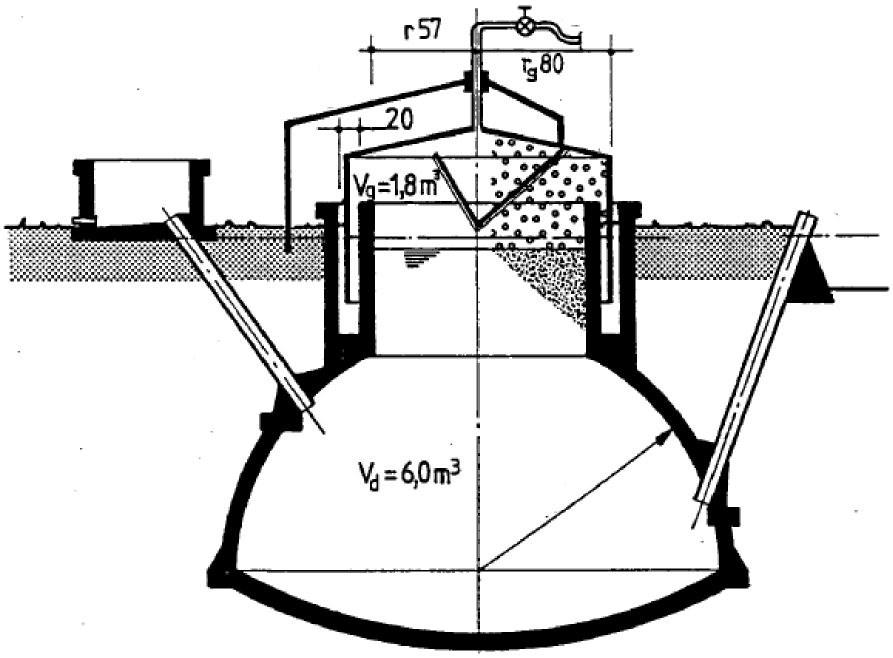



**Figure 5: CARMATEC fixed dome plant**
***Source: Thom (1994).***

The Centre for Agricultural Mechanization and Rural Technology (CAMARTEC) have modified the GB/T4750-2002 fixed dome Chinese design to Figure 5 in order to complement the Tanzanian environment and several countries have adopted this approach (Mulinda *et al*., 2013). This modification uses underground brickwork vessel deposit, fermentation compartment and a dome on the surface of the ground that store the gas produced. Mulinda *et al*. (2013) state that the CAMARTEC design combines the gas holder with the fermentation compartment as illustrated in Figure 5. Some fixed dome designs include the Deenbandhu and Deenbandhu 2000 model established in India (IRENA, 2016).

### 2.6 The floating drum biodigester plant

Mulinda *et al*. (2013) note that the floating drum plant is an Indian prototype that was developed in 1930. In 1962, this design was widely accepted in other regions like Khadi and Village Industries Commission (KVIC) where the digester compartment is made of underground brickwork with cement plastering. This system has dual structures for gas, one for generating gas and the other for collecting (Mulinda *et al*., 2013).

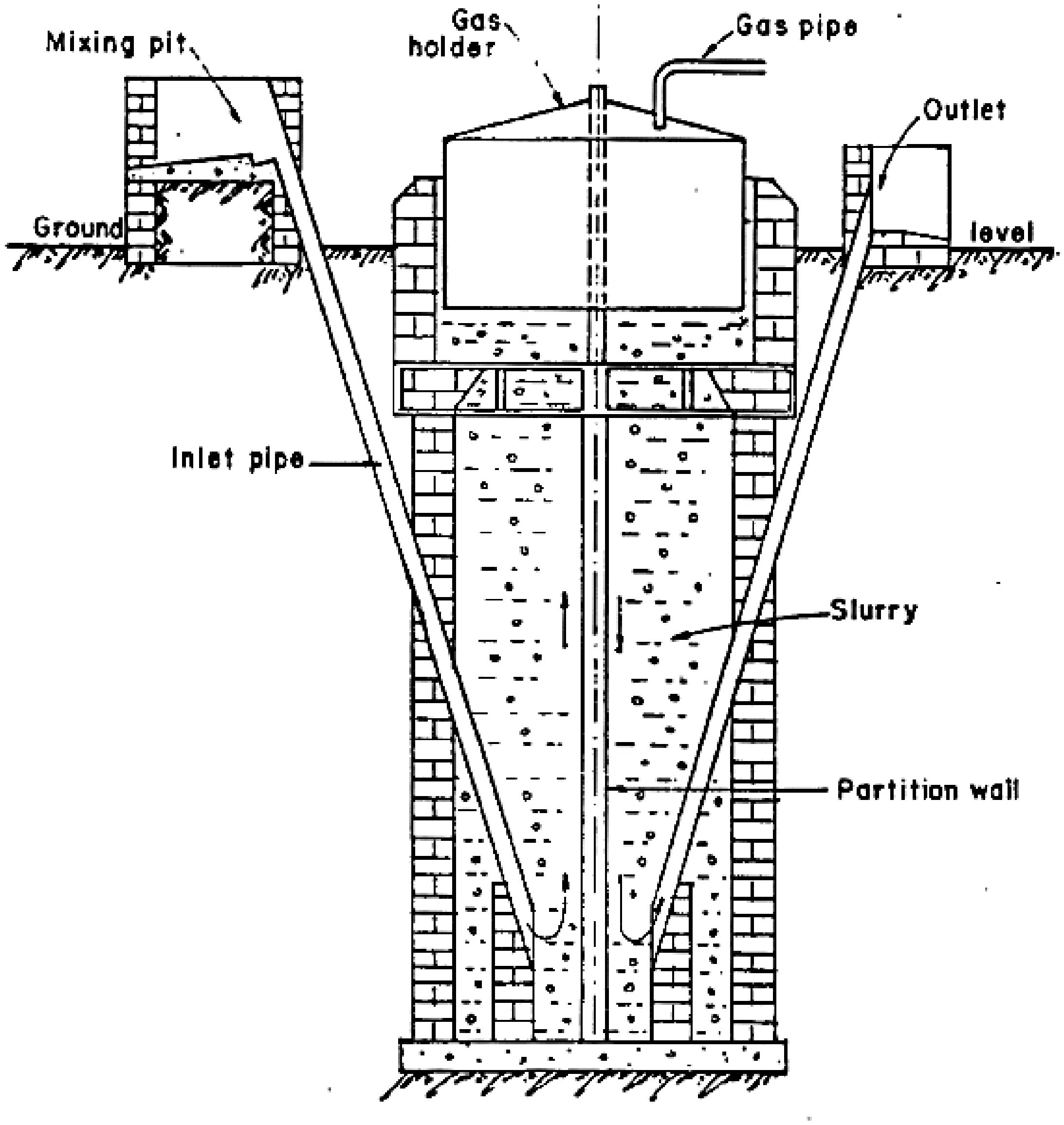



**Figure 6: Floating drum biodigester plant**

***Source: Thom (1994).***

The floating drum biodigester system design illustrated in Figure 6 has a mixing tank located above the ground and a digester tank constructed deep underground (Singh, 2010; IRENA 2016). Singh (2010) demonstrates that a floating system that has two cement pipes, one for the inlet (where the system is fed the slurry) and the other for the outlet (where the slurry is passed out). The original feeding is left for two months to allow the bacterium formulation inside the slurry. The outlet pipe is used for draining spent slurry and overflows from this system, whereas, the inlet pipe is only used for feeding the system. Singh (2010). The gas holder illustrated by the steel drum cap above is used to manage excess gas and it can float (move up and down). This system also has an outlet pipe over the metallic cap that can be connected to a gas stove where the gas is drawn. After sufficient biogas is generated, the pressure exerted by the biogas drives the expanded slurry into the outlet chamber and it will then run-off into the overflow tank while the spent slurry is later used as manure for plants (Singh, 2010). The gas is extracted through the central guide above this system, which is opened when the supply of biogas is required (Mulinda *et al*., 2013; Singh, 2010). To ensure that the bacterium does not die, continuous feeding of this system is recommended. If this is process is not followed, the bacteria dies and no gas is produced. This system is expensive, requires maintenance and the metallic drum rusts over time. "The African Biogas Partnership Programme has backed the fixed dome design. This is because the fixed dome design is robust, can be prefabricated (which has advantages for obtaining credit, as the prefabricated unit represents a resource that can be claimed back by the creditors on the borrower defaulting on payments)" (DfID, 2011).

## 2.7 The balloon biodigester plant

**Figure 7: Balloon biodigester plant**
***Source: Muvhiiwa et al., (2017).***

According to IRENA (2016) balloon digester plants illustrated in Figure 7 are very common in Latin America, and are normally manufactured using solid elastic material. Gas extraction in this system is through joining gas drawing pipes into the balloon. The inlet and the outlet pipes are utilised for feeding and draining out the slurry (IRENA, 2016). Vögeli (2014) recommends that a balloon digester should be placed underground in order to increase its lifespan.

## 2.8 The South African plastic biodigester plant (Biogas-Pro)

Cheng *et al*. (2014) reveal that Prefabricated Biogas Digesters (PBDs) are common in a number of African countries including South Africa. Previously PBDs were imported from China, however, South Africa currently manufactures its own PBDs called Biogas-Pro, shown in Figure 8. The Biogas-Pro can be installed with a gas monitoring device. In addition to this, Biogas-Pro can be connected to household sewage pipes to collect affluent. Furthermore, organic waste is easily fed into an entry that opens and closes easily.

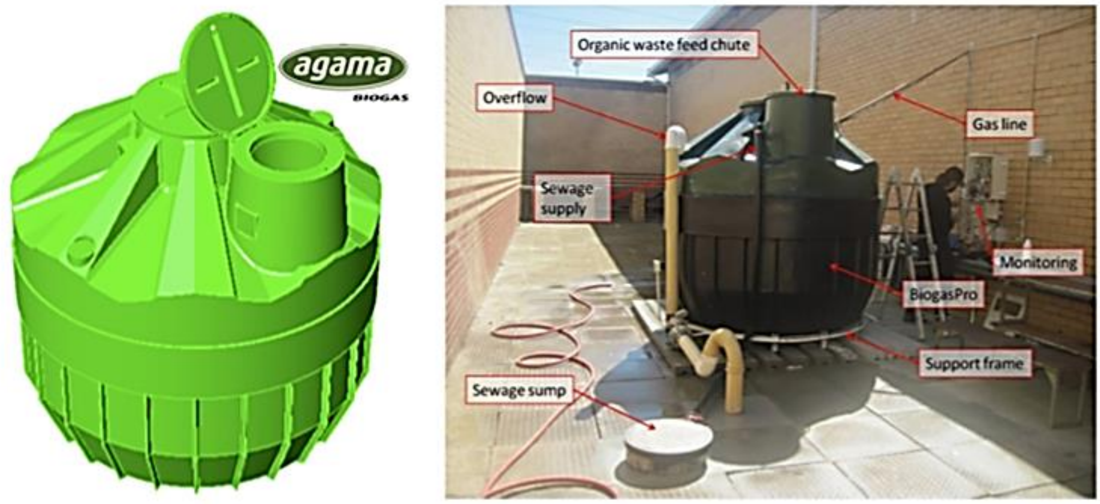



**Figure 8: PBDs SA Agama Biogas-Pro design**

***Source: Cheng et al., (2014).***

## 2.9 Other biogas digester designs

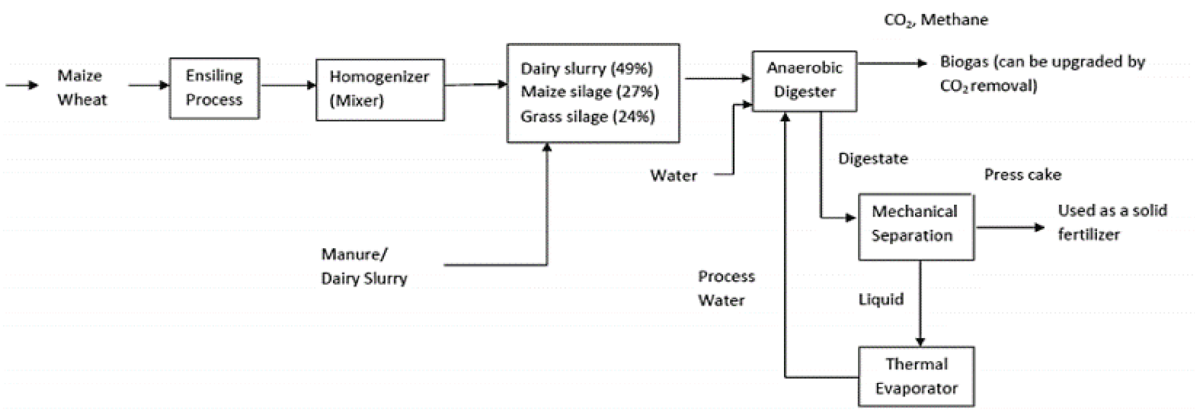



**Figure 9: Multifaceted biodigester plant**

***Source: Haig & Gorgens (2013).***

Figure 9 biodigester illustrates a common structure of systems frequently utilised in Europe and America. This type of a digester caters for manure and waste treatment process. The multifaceted biodigester allows biogas yields to be increased by adding silage and food waste into the digester. The accurate balancing of carbon and nitrogen ratios improve conversion process based on the content of the feeds (Haig & Gorgens, 2013).

The most suitable biogas designs are dependent on various factors such as cost, technical specifications, end-user, institutional and environmental factors. Technical specifications refer to water tightness, gas production efficiency, gas pressure, water requirements, temperature sensitivity, foam release, sedimentation, superstructure wear and tear, and co-digestion ability (DfID, 2011). Several biogas digester designs can be assigned a qualitative score depending on the biogas system efficiency with regards to technical factors, and fixed dome biogas digesters are leading in terms of technical consideration. DfID, (2011) describes the financial implications associated with biogas digester systems as capital cost, operational cost and alternative fuel cost.

According to DfID (2011), the flexible plastic design is the most suitable digester to be considered, however, access to finance allows the other biogas types to be equally competitive since it is less complex to obtain credit for the floating drum and fixed dome household biodigester.  Therefore, end-users have a choice in terms of the digester design that they prefer utilising.

### 2.10 Classification of anaerobic digestion systems parameters

According to Haig & Gorgens (2013) anaerobic digestion process can be classified utilising a number of techniques mainly:

- **Temperature**

The temperature is normally required to be 25 – 45°C (mesophilic) or 50 – 60°C thermophilic Haig & Gorgens (2013). Gagnon *et al*. (2014) describe the two main types of bacteria categories for anaerobic digestion process, the first one being the mesophilic bacteria which contains a wide range of species that favour an average temperature of 35°C. The second type, thermophilic, refers to extremophiles that favour a typical temperature of 55°C (Kim, 2002). Thermophilic bacteria have a faster metabolic rate allowing them to process the organic influent faster, but extremophiles are a smaller specialized category of bacteria that are only stable under high-temperature conditions. Kim (2002) further explains that disturbance of the vessel temperature can negatively affect the bacteria content inside the digester, this means that metabolism can be inhibited, thus reducing the digester efficiency. The thermophilic bacteria have minimal flexibility and therefore are very sensitive to conditions taking place inside the digester vessel. As a result, a thermophilic biodigester needs an additional maintenance time from the operator (Kim, 2002).

**Table 3: Thermal and retention time description**

***Source: (Al Seadi et al., 2008).***

| Thermal stage | Process temperatures | Minimum retention time |
|---|---|---|
| Psychrophilic | < 20 °C | 70 – 80 days |
| Mesophilic | 30 – 42 °C | 30 – 40 days |
| Thermophilic | 43 – 55 °C | 15 – 20 days |

Table 3 highlights the importance of the temperature constancy for an effective anaerobic digestion process. The active digester operational temperature indicated in Table 3 is selected based on the feedstock resource that is used (Al Seadi *et al.*, 2008). Various biogas yields that are produced over a specific number of days in different climate conditions and retention time are illustrated in Figure 10: Biogas yields dependent on different temperatures and retention rate (LfU).

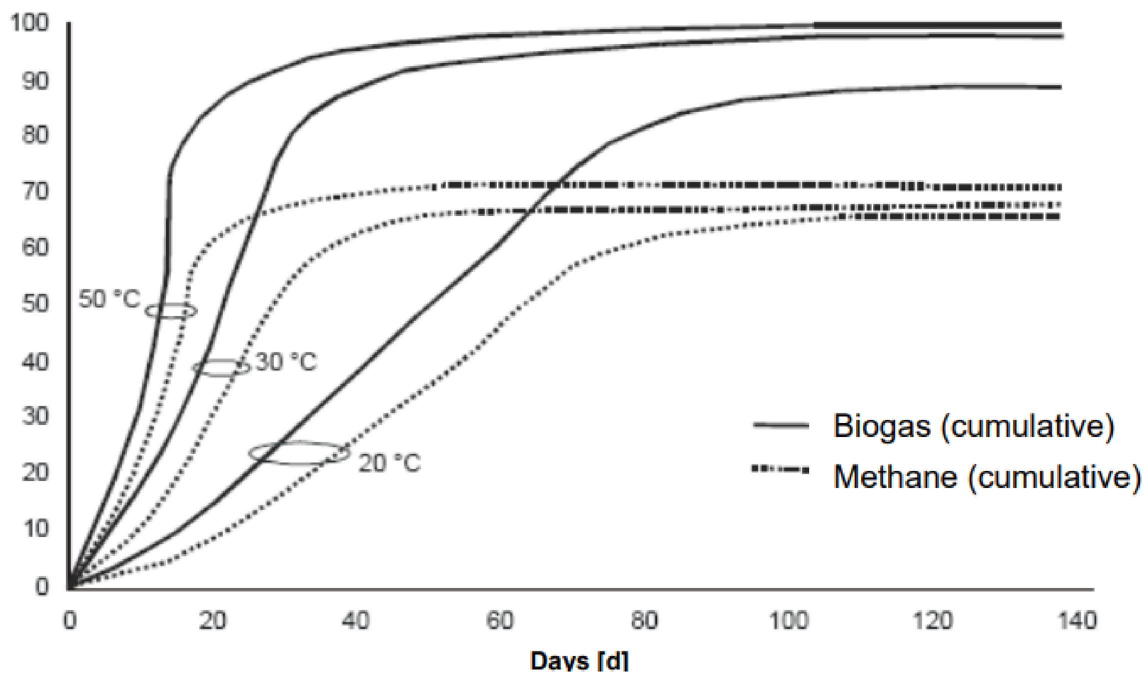
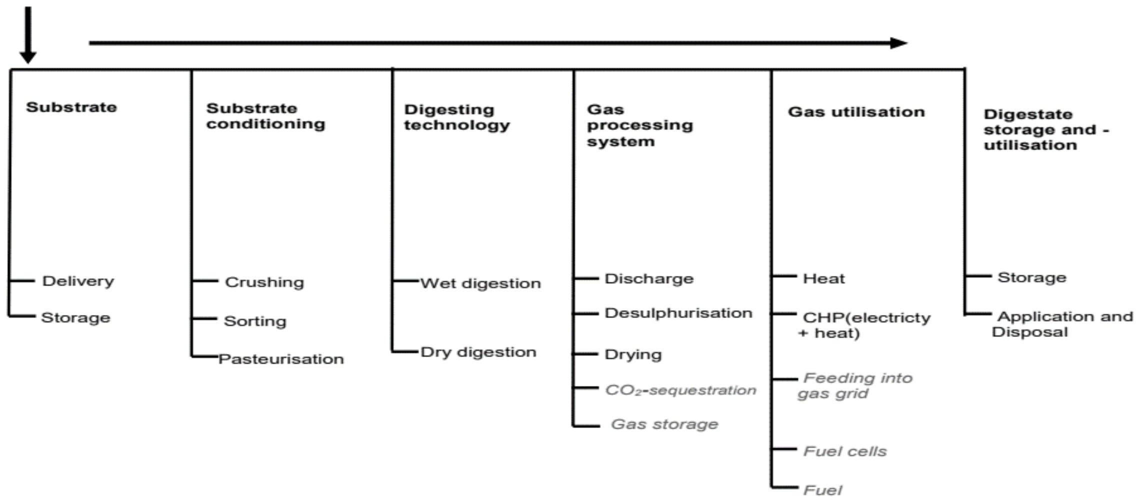



**Figure 10: Biogas yields dependent on different temperatures and retention rate (LfU).**
***Source: Al Seadi et al., (2008).***

- **Wet or dry matter**

The main process steps in the biogas generation process are illustrated in Table 4. The difference between wet and dry AD is hypothetical, this is mainly due to the microbiological procedures always transpiring in liquefied nature. The “pumpability” regulates whether the digester will utilise a dry or wet digestion approach (Al Seadi *et al*., 2008). Haig & Gorgens (2013) explains that wet AD has between 5 – 15% dry matter while the dry AD system has over 15% of dry matter. Al Seadi *et al*. (2008) concluded that a direct supply of dry feeds will certainly increase the dry matter content in the biodigester vessel. Several feeds can be utilised for producing biogas. The feedstock ranges from animal manure, organic waste from our households, food industries, harvest residues, agro-processing, waterborne waste, sludge, municipal solid waste (Al Seadi *et al*., 2008). One of the unique strength of biogas is its ability to use “wet biomass” feedstock with a moisture content between 60 – 70%, this refers to feeds such as sewage and animal slurries among others (Al Seadi *et al*., 2008).

**Table 4: The main process steps in a biogas plant**
***Source: (Al Seadi et al., 2008).***




## 2.11 The digester configuration

Haig & Gorgens (2013) highlights the following biodigesters formulation methods:

- Completely mixed digester (CSTR)
- Up-flow anaerobic sludge blanket (UASB)
- Covered Lagoon
- Fed-batch digester (optional mechanical mixing)

- Plug flow digester (PF)
- Rotary mixed plug flow digester (MPF)

### 2.12 Gas production from different feedstock

Gas production yields involved in a biodigester are dependent on the digester design and the type of feedstock. Some feedstock, digester designs and the gas yields are influenced by various operational parameters such as "pH (acid-base concentration of the slurry), the Hydraulic Retention Time (HRT) and agitation" (Colombo *et al.*, 2013). Different feedstock produces varied gas yields which range between 300 and 500 litres of biogas per kilogram (Colombo *et al.*, 2013).

**Table 5: Biogas production and gas yields from various feedstock**
***Source: (Colombo et al., 2013).***

| **Substrate** | **Daily Production kg/animal** | **% DM** | **Biogas Yield $m^3$/kg DM** | **Biogas Yield $m^3$/ Animal/day** |
|---|---|---|---|---|
| Pig Manure | 2 | 17 | 3.6 – 4.8 | 1.43 |
| Cow | 8 | 16 | 0.2 – 0.3 | 0.32 |
| Chicken | 0.08 | 25 | 0.35 – 0.8 | 0.01 |
| Human Excreta | 0.5 | 20 | 0.35 – 0.5 | 0.04 |
| Grass | - | 80 | 0.35 – 0.4 | - |
| Water Hyacinth | - | 7 | 0.17 – 0.25 | - |
| Maize | - | 20 | 0.25 – 0.40 | - |
| Rice Straw | - | 87 | 0.18 | - |
| Rice Husk | - | 86 | 0.014 – 0.018 | - |
| Bagasse | - | - | 0.165 | - |

Leaf Meter 0.6 ($m^3$/kg DM)

DM = Dry Matter, a = based on mean biogas yield ( $m^3$/kg DM)

Based on the laboratory analysis indicated in Table 5, biogas yields vary amongst a diverse range of feedstock (Colombo *et al.*, 2013). Pig manure, as illustrated in Table 5 holds better biogas yields compared to that of cows, chicken and human waste. By contrast, crop feedstock yields lesser biogas per cubic meter with a fairly high dry matter respectively (Colombo *et al*., 2013). The South African government indicated that maize could not be used in the production of biofuels, in order to encourage food security (Brent, 2014). The assumption here is that feedstock that could threaten food security are not feasible for generating biogas in the context of South African policy regime, therefore, rice and maize are perceived as an inappropriate feedstock. According to Al Seadi *et al*. (2008) various factors such as species, sex, animal age, as well as geographical and climate conditions affect the composition of animal manure in biogas digestive system.

**Table 6: Quantity of dung required for various plant sizes**

***Source: (Singh, 2010).***

| Size of plant (gas production/day) | Amount of wet manure required (kg) | Number of animals |
|---|---|---|
| 2 | 35 – 40 | 2 – 3 |
| 3 | 45 – 50 | 3 – 4 |
| 4 | 55 – 60 | 4 – 6 |
| 6 | 80 – 100 | 6 – 10 |
| 8 | 120 – 150 | 12 – 15 |
| 10 | 160 – 200 | 16 – 20 |

**Table 6: Quantity of dung required for various plant sizes**
Source: (Singh, 2010).provides a clear illustration of the quantity of dung required for various sizes of biogas plants. This illustration focuses more on kilograms and a number of animals required for a range of biogas plants rather than the source, however, Colombo *et al*. (2013) demonstrate that different feedstock produces varied gas yield.

### 2.13 The shortfall on the biodigester rollout techniques

Micro-scale biodigester technology utilisation has significantly increased in Asia although the uptake in Sub-Saharan Africa has up to now been sluggish regardless of important national and international efforts aimed at supporting biogas technology adoption (DfID, 2011). There are various reasons for this slow-moving development in household biodigesters. These are primarily, shortages in feedstock; this is linked to relatively low numbers of cattle in the African continent when compared to India and China who produce 28% and 19% of cattle globally (DfID, 2011). Another challenge in the uptake of household biogas digesters is the unavailability of land and water. However, community water supply challenge has been addressed through the World Bank programme that includes rainwater collection techniques. Such mechanisms have a very strong potential to increase the uptake of household biogas digesters. Another reason for a minimal uptake of household biodigesters is the lack of proficiency and awareness on the important benefits that come with the adoption of biodigesters. Micro-scale household biogas digesters are an emerging technology that has continuous programmes in several Sub-Saharan African countries, while they have been implemented in many countries worldwide. There is a need for further research that will ensure that small-scale household digesters have longevity, safety standards and sustainable implementation (DfID, 2011). The provinces that have sufficient livestock for biogas production are shown in Table 7.

**Table 7: Identified domestic and communal digester project options**

***Source: (Hugo, 2016; Stats SA, 2011).***

| | | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|---|
| Eastern Cape | Amathole | 48 632 | 3.5 | 9 726 | 95 219 | 19% | 17 832 | 55% |
| Eastern Cape | OR Tambo | 18 881 | 1.36 | 3 776 | 30 977 | 68% | 21 063 | 18% |
| Mpumalanga | GertSibande | 26 560 | 1.91 | 5 312 | 41 795 | 49% | 20 451 | 26% |
| Mpumalanga | Ehlanzeni | 25 725 | 1.85 | 5 145 | 55 095 | 33% | 18 166 | 28% |
| Limpopo | Vhembe | 58 695 | 4.22 | 11 739 | 125 531 | 66% | 82 606 | 14% |
| Limpopo | Greater Sekhukhune (1) | 84 125 | 6.05 | 16 825 | 95 186 | 43% | 40 994 | 41% |
| Limpopo | Greater Sekhukhune (2) | 30 536 | 2.19 | 6 107 | 62 313 | 62% | 38 635 | 16% |
| Limpopo | Mopani | 74 043 | 5.32 | 14 808 | 72 658 | 34% | 24 844 | 60% |
| Kwazulu-Natal | Uthukela | 33 085 | 2.38 | 6 617 | 64 810 | 34% | 22 019 | 30% |
| Kwazulu-Natal | Zululand | 19 121 | 1.37 | 3 824 | 27 663 | 77% | 21 423 | 18% |
| **Total** | | **419 403** | **30.15** | **83 879** | **671 247** | **46%** | **308 032** | **27%** |

[A] Rural organic waste allocated to digester by feasibility modelling

[B] Typical power available from digesters in the area of assessment

[C] Number of digesters required

[D] Number of low-income households in the area of assessment

[E] Households using cattle dung in the area of assessment - StatsSA (2011)

[F] Potential users (households) estimated as [D]X[E]

[G] Digesters as a percentage of potential users [C]/[F], on average 0.35kW per digester

According to Hugo (2016), the potential for household and communal biodigesters is significant, as illustrated in Table 7. Households that can utilise biodigesters represent a third of the total rural communities that require access to clean energy. According to Hugo (2016) selected districts and regions can be strengthened by accumulating cow dung and various biomaterial feeds. Understanding the distribution of cattle in rural areas is a complex process, however, Stafford (2013) projected an extensive cattle populace in several provinces illustrated in Table 8. The leading provinces in terms of the cow dung as a feedstock is KwaZulu Natal and the Eastern Cape. Rural communities that have a potential to host micro-scale biodigesters represent about 45% of cattle ownership with a total cattle estimate of 3.2 million (Stafford, 2013).

**Table 8: Extensive cattle population**

***Source: (Stafford, 2013).***

| **Province** | **Number of households with 4 or more cows** | **Total number of rural households** | **Percentage of rural households with biogas potential** |
|---|---|---|---|
| Eastern Cape | 224 417 | 692 775 | 15.8 |
| KwaZulu-Natal | 310 206 | 963 835 | 16.5 |
| Limpopo | 47 727 | 765 089 | 1.8 |
| North West | 27 740 | 362 091 | 3.1 |
| Mpumalanga | 22 327 | 359 240 | 2.8 |
| Free State | 22 770 | 132 736 | 4.9 |
| **Total** | **655 187** | **3 275 766** | **44.9** |

The South African bioenergy Atlas was launched in 2017 with an objective to recognise sustainable bio-energy projects. South Africa has a strong potential in the bio-energy sector, however, this strong point has not yet been tapped into at full scale (Cambell, 2017). Table 8 shows cow dung available in over 6 provinces where nearly 45% of micro-scale biogas could be produced.

### 2.14 Technical constraints for micro-scale biodigesters

The technical constraints indicated by (Colombo *et al*., 2013) are as follows:

- **Climatic conditions**, which will determine the micro-scale biogas digester operating temperature range.

- **Availability of the feedstock**, in order to estimate biogas that can be produced.
- **Availability of water**, to ensure that the households are able to prepare the required amount of slurry.
- **Local construction materials**, to ensure that the cost of micro-scale biogas digesters is affordable to the target end-users.
- **Local technical capacity**, with the aim to construct, operate and maintain the biodigester rigorously using local skills that will gradually be capacitated.

### 2.15 Non-technical Constraints for micro-scale biodigesters

The non-technical constraints alluded by (Colombo *et al*., 2013) are as follows:

- Level of disposable income for targeted end-users
- Availability of subsidies
- Availability of loan facilities
- Availability of alternative energy sources (cost)
- Financial Constraints

### 2.16 Environmental Spinoffs

Environmental challenges that could be resolved through the adoption of biodigester utilisation consist of "sanitation, air quality, condensed deforestation, and nutrient supply to crops, carbon sequestration in soil and the use of digester slurry as fish food". The results on environmental paybacks for a number of biodigester designs is anonymous hence more research on specific design is needed (DfID, 2011). In rural areas, drying manure is regarded as a flawless source for dealing with flies of all types (Sorathia *et al*., 2012). Poverty is one life-threatening reason that promotes the use of "animal dung, crops wood and charcoal" as a source of fuel in poor communities. Consequently, smokes such as, "(PM2.5, PM10, inhalable dust, respirable dust), carbon monoxide (CO), airborne endotoxins (inflammatory agents), and other toxic chemicals (PAHs, Arsenic, Aldehydes, Nitric Oxides, Benzene and Sulphur Dioxide)" affects household air quality standard (DfID, 2011). Biodigesters can play a significant role in displacing and improving the indoor air quality standard and there is a need to quantify the actual improvements in household air quality realised through displacing firewood and other flammable substances with biogas (DfID, 2011). In areas where biomass is a primary source of energy, residents often seat around an indoor cooking stove or open fire that emits enormous amounts of pollutions. Unambiguously, in Sub-Saharan Africa, this is commonly a task assigned to women and children (Brown, 2006). Most women see to it that housework, including cooking, is always prepared for their families, as a result, they are more exposed to cooking stove smoke than men. In 2000, 3 – 4% of global mortality rates were associated with the burning of fossil fuels, whereas, indoor air pollution arising from biomass burning was also reported to increase breathing problems for children, low birth weight, asthma and, lung infections for adults (Brown, 2006).

"Clearly, biogas—being free of smoke—offers dramatic improvement of this particular health problem. Even so, concerns among potential users about other health risks of biogas generation have impeded more widespread adoption of the technology" (Brown, 2006). While biogas can play a meaningful role in reducing the negative impacts alluded already, human and animal waste contains a significant amount of pathogens and a number of Cryptosporidium (Brown, 2006). The dominance of pathogens can cause diarrhoea, stomach cramps, dehydration, fever, and vomiting, while in vulnerable populations such as infants, children, the elderly, and immune-compromised persons, it can result in deaths. Biogas generally reduces pathogens loads, however, handling biogas slurry or utilising it as a fertiliser can originate hazardous illnesses. Separating the digestion process into discrete acidifying and methanogenic stages and isolating the acidogenic bacteria into their own tank results in complete eradication of live pathogens (Brown, 2006).

The adoption of micro-scale biodigester is frequently allied to lower deforestation rates, however, that is not always the case, especially in instances where biogas is not considered as an energy provision technology (DfID, 2011). In the main, fuelwood is obtained from forests that are being cleared for agricultural purposes, whereas, dead and fallen wood is normally collected as an alternative to living plantations and this approach encourages forestry protection. Firewood supplies are also accessible from agroforests, though, animal dung and a number of crops avail alternative for biogas feedstock (DfID, 2011). Biogas produced has a high caloric value (21–37.5 $MJ/m^3$), and has no smoke and pollution (Singh, 2010; Colombo *et al.*, 2013). It is economical, it has no residue, it can be supplied through pipelines, it can also be used as domestic fuel and for electricity generation objectives (Singh, 2010). The environmental and medical problems indicated in this chapter provides a substantial opportunity for the biogas technology to be adopted. Biogas application for households can assist in combating hazardous smokes that are normally atmospheric. This can be achieved by utilising the same biomass feedstock that is normally burnt to generate energy. The same feedstock can then be used for cooking purposes through a biogas digester. Access to electricity is very limited in informal and rural areas which are normally very remote and difficult to access (Sorathia *et al*., 2012). Furthermore, residents staying in these areas are extremely poor, making it highly unlikely that they will ever be able to afford to pay for electricity even if they are connected to the national grid. Due to financial impracticality and budget constraints of setting up electricity distribution infrastructure in these areas, it is highly likely to not have access to basic energy services (Sorathia *et al*., 2012).

## 2.17 Economic and social drivers for cooking through micro-scale biogas digester.

The biogas has variable benefits that vary from country to country and even between societies and households. According to Colombo *et al*. (2013) economic and social benefits of micro-scale household biogas digesters can be summarised as follows:

**Economic**

- Reduction in expenses for chemical fertilizers in agriculture;
- Increased agricultural yields
- Creation of employment
- Alleviation of poverty
- Cost and time saving from firewood
- Increased income and employment from integrating cattle rearing and farming

**Social**

- Time-saving for women
- Reduction of drudgery for women

Biogas is considered by many experts to be an exceptional tool for improving life, livelihoods and health in developing countries. Micro-scale biogas digesters are usually manufactured using concrete, bricks, metal, fibreglass and plastic. The manufacturing material used is likely to create jobs and stimulate economic growth (Brown, 2006).

## 2.18 Status of micro-scale biogas in South Africa

Many developers recognise that biogas potential lies within the rural dwelling owing to many communities that do not have access to electricity, and even those with access find cooking with electricity expensive and would opt for an alternative fuel source. Households with a sufficient number of livestock are able to have biodigesters that can serve as an alternative energy source for thermal energy needs. There are initiatives that were implemented by the government to ensure that biodigesters rollout is realised in rural communities. The South African National Energy Development Institute (SANEDI) is responsible for managing and rolling out the Working for Energy Programme 15, this renewable energy initiative is mandated to provide thermal energy and improving the quality of life for people in rural communities. There are three micro-scale biodigester initiatives that SANEDI implemented in 2015. This included the Melani Village Biogas Expansion Project; the Illembe District digesters and the Mpufuneko Biogas Projects. The Melani Village Biogas Project in the Eastern Cape was developed in partnership with the University of Fort Hare for installing110 biodigesters (GIZ & SABIA, 2016). The Illembe District Biogas Project in KwaZulu-Natal installed of 26 micro-scale digesters. In Limpopo province, the Mpufuneko Biogas Project installed 55 micro-scale biodigesters. The Khanyisa Projects is a renewable energy developer that was contracted to train local builders to construct 26 six cubic meter digesters.

GIZ & SABIA, (2016) indicates that a number of developers were contracted for constructing these micro-scale digesters. This included companies like Biogas-Pro Agama, Finishes of Nature and BiogasSA. Biogas-Pro Agama has developed over 320 units to date for various clients including, bush camps, wine and game farms, rural households and schools (GIZ & SABIA, 2016). Their projects are mostly situated in the Western Cape with a few in the Eastern Cape and Kwa-Zulu Natal. They construct different digester models and sizes depending on the requirements of the client and feedstock availability. The installation duration for smaller units takes between 2 and 3 days. This type of micro-scale design processes about 5kgs – 20kgs of waste daily. Total project costs are on average in the region of R32 500 – R40 000, with an installation cost of R20 000 as well as R5 000 for the necessary connections (GIZ & SABIA, 2016; Ruffini, 2013).

The impetus to establish a fully-fledged functioning biogas industry is slow. This is recognised through approximately 400 biodigesters installed in South Africa (Tiepelt, 2015). In 2013, only 38 digesters were registered with Nersa, this displays a high degree of non-compliance with the Gas Act 48 of 2001 (Kolver, 2013). According to SABIA (2013) there is a collection of a few organisations that are effectively promoting the biogas development in South Africa. These organisations include among others, SABIA, SANEDI, Biogas SA, REI4P participants as well as the academic research that is implemented through South African universities (Roopnarain

& Adeleke, 2017). The REI4P have channelled private investment towards the development of larger scale renewable energy in South Africa.

### 2.19 Biogas employment opportunities in South Africa

GIZ & SABIA (2016) utilises an excel based input-output model to aggregate biogas project pipeline data to determine the employment factor for each type and phase of a biogas AD project i.e. large, medium, small and rural projects illustrated in Figure 11, through the phases of feasibility, development, construction, operation and maintenance.

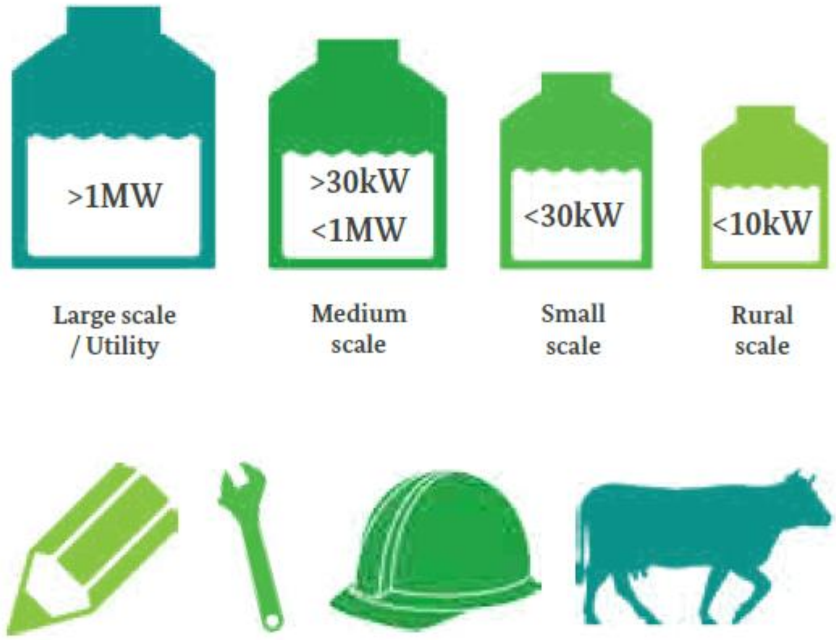



**Figure 11: Biogas digester development, construction and maintenance & operations.** ***Source: GIZ & SABIA (2016).***

Figure 12 specifies the level of skills required to operate a micro-scale biodigester. At the feasibility stage and project preparation, only skilled individual can operate at this level. This means that rural dwellers are not at liberty to decide on their on to install a digester. Unskilled labours can only participate during construction. After this, only the services of semi-skilled are required. This challenge in the context of South African rural areas has contributed to a very high degree of digester failure already discussed.

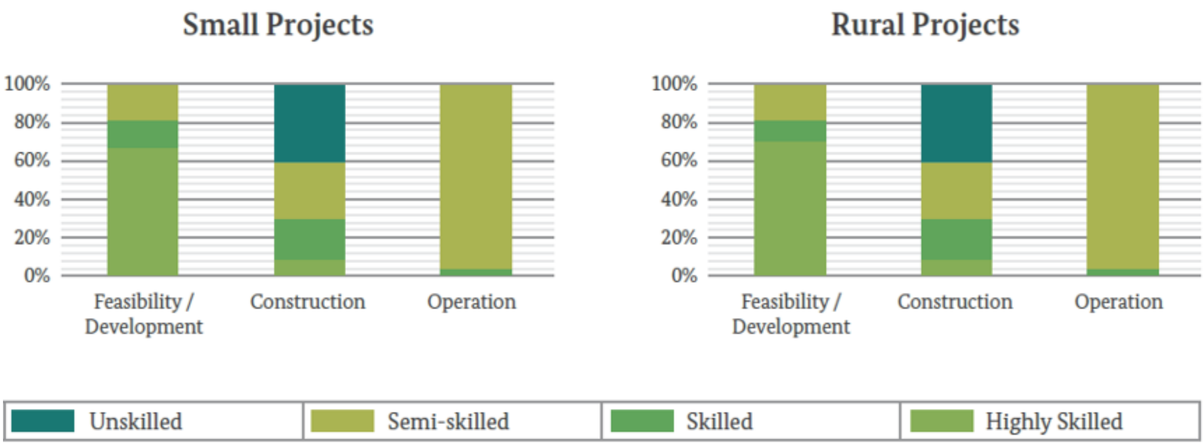



**Figure 12: Skills required for operating a micro-scale biodigester**

***Source: GIZ & SABIA, (2016).***

### 2.20 **Electrification Status in South Africa**

Most of the employment opportunities created by micro-scale digesters are within the construction, maintenance and operations. Figure 11. According to Stats SA (2009), 35% of South Africa's population lives in rural areas. The Integrated National Electrification Programme (INEP) of 2016/17 provides policies and guidelines for undeclared areas, farm-houses and non-grid households (GIZ & SABIA, 2016). The South African utility is unable to recover electrification cost from rural areas, as a result, it has projected that pulling power line to remote scattered areas would not be financially viable (GIZ & SABIA, 2016). This quandary offers an opportunity for other alternative energy provision technologies. Stats SA (2014) General Household Survey analysed about 15.6 million households throughout South Africa. The analysis found that approximately 85.4% of households in South Africa have access to electricity. This means that there are about 2 million households without access to the national grid. These households are generally located in rural areas which makes it difficult to connect to the grid and therefore depend on alternative fuel sources for their basic energy needs. While mainstream households are electrified, electricity cost has continued to increase and many end-users choose to utilise a more economical fuel source for cooking (Stats SA, 2014). StatsSA (2009) presented about 441 000 households using solid fuels, for instance, charcoal and firewood for cooking and heating, regardless of their electrification status. StatsSA (2014) reported that around 5.6 million households do not have municipal refuse removal system in place, while over 3 million households live in surroundings of poor sanitation, lower than the standard allocated to the Reconstruction and Development Programme (RDP). A 4 – person household sewage and organic waste alone would not be sufficient to run an AD (GIZ &

SABIA, 2016). However, two or more households may jointly feed an AD, and share the resulting biogas cooking hours. Nonetheless, adding manure from livestock would make a single household AD viable.

# CHAPTER 3

# 3. METHOD AND APPROACH - FOR THE ANALYSIS AND DISCUSSION OF A SUSTAINABLE OPERATIONAL METHOD FOR MICRO-SCALE BIODIGESTER

This Chapter focuses on the research method and approach technique that was used for developing a sustainable operational method for a micro-scale biodigester in South Africa. The detail methodological approach is discussed in Chapter 4. The analysis for a micro-scale biodigester failure was investigated through the inspection of the following factors that affect the lifespan of a digester:

- Lack of technical skills;
- Human error;
- Lack of digester operational training;
- Appliance and mechanical failure;

## 3.1 Project development approach

Secondly, the project development process and integration into community structures were developed to ensure a sustainable operation for micro-scale biodigesters. This approach covers the following factors:

- Stakeholder consultation;
- Basic energy needs analysis;
- Local community skills assessment;
- Problem solving techniques for micro-scale digesters;
- Strategies to address barriers for project implementation;
- Project preliminary designs;
- Project final designs;
- Project construction and commissioning.

## 3.2 A sustainable operational method for a micro-scale biodigester in South Africa is investigated

Thirdly, a sustainable operational method for micro-scale biodigesters is proposed. The proposed sustainable operational method emanates from identified root causes of micro-scale biodigester failure. The proposed sustainable operational method entails the following:

- Compulsory biodigester daily feeding;
- Compulsory biodigester routine maintenance;
- Compulsory digestate collection;
- Biodigester breakdown call centre/ customer care.

## 3.3 Analysis of an economic and market model

Lastly, an evaluation of the micro-scale biodigester, an economic and market model was conducted. The assessment involved the following factors:

- Existing micro-scale biodigester costing model;
- Poverty alleviation through the adoption of micro-scale biodigester;
- Policy review for micro-scale biodigesters in South Africa.

## 3.4 Limitations

South African rural areas are located in diverse remote areas and some rural provinces where unreachable. As a result, it was not possible to investigate all rural communities that exist in South Africa. Qauntec easy data is a data tool that was utilisation to analyse economic parameters in rural areas.

## 3.5 Analysis administration

Conversation with rural dwellers that have micro-scale biodigesters was conducted in African languages. During the oral translations, words such as biogas and “digester” were not translated as they do not exist. Where site visits were not practical, discussion with a representative that worked on the projects was held in order to obtain insight.

**CHAPTER 4**

# 4. ANALYSIS AND DISCUSSION OF A SUSTAINABLE OPERATIONAL METHOD FOR MICRO-SCALE BIODIGESTER

The research project was designed to develop a sustainable method for operating micro-scale biodigesters. The analysis and discussion examined the factors affecting the lifespan of biodigesters and biogas production process. Hereafter, an operational method for South African micro-scale biodigester is developed, followed by an analysis of economic and market model and the existing policy framework and gaps. This will assist in the development of a sustainable operational method for a long-lasting domestic usage of micro-scale biodigesters in South Africa. According to Kitchen and Tate (2000), the process of gathering information in order to enhance an understanding of relationships between the environment and human beings encourages detailed research in specific areas, in this instance, a sustainable operational method for micro-scale biodigester in South Africa. Section 4.1 covers the analysis of factors affecting the lifespan of a biodigester and industry experience of the author, in cases where the information is sourced elsewhere, it is cited accordingly.

## 4.1 Lifespan analysis of a micro-scale biodigester

The analysis of the small-scale biogas projects case study conducted in the Eastern Cape Province highlighted that about 65% of all digesters incorporated in the analysis was no longer operational (GIZ, 2016). There are problems in terms of operating micro-scale biodigesters successfully. The age of digester installation influences the lifespan duration and sustainability. Understandably, a majority of the digester covered by GIZ (2016) were structurally and mechanically solid, clearly eliminating causes of failure to be directly linked to poor quality of product or workmanship. Figure 13 covers five possible root causes for digester failure in South Africa, this is discussed in section 4.1.1– 4.1.6.

According to (Parawira, 2009), economic factors that affect biogas production and commercialisation are as follows:

- Cost of biomass feedstock, which differs among countries depending on land availability, agricultural productivity and labour costs;
- Biogas production costs, which depends on the plant design, project site, size and technology;
- The cost of fuels that are used in the absence of biogas.

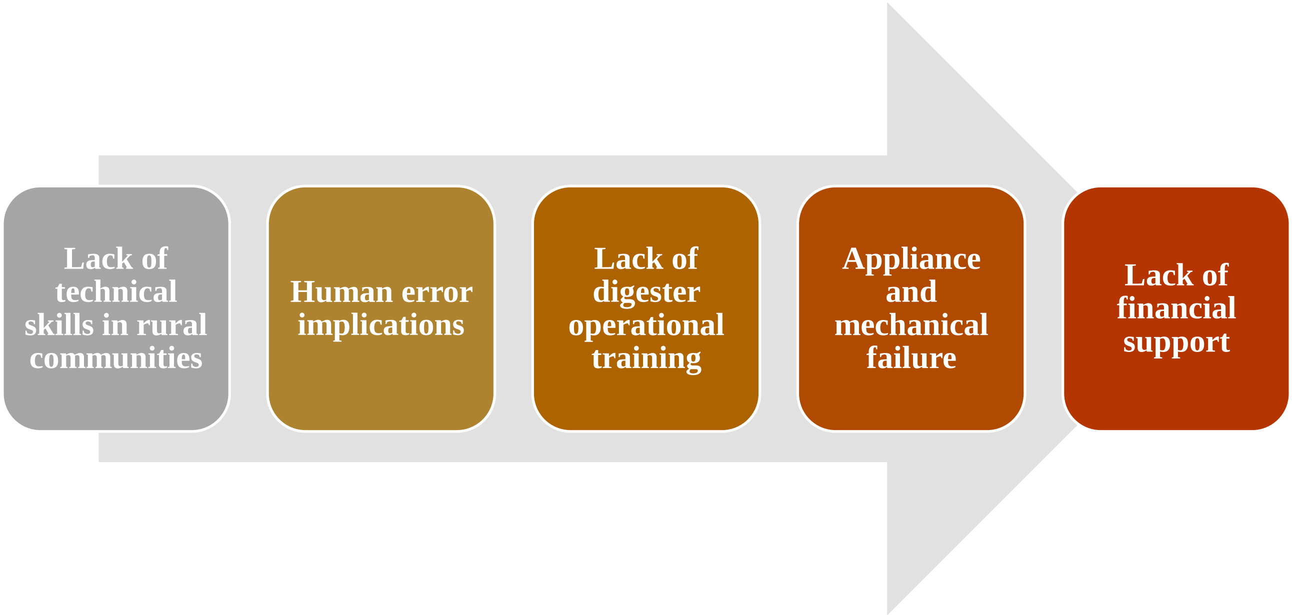



**Figure 13: Factors affecting the lifespan of a micro-scale**

### 4.1.1 Lack of technical skills in rural communities

Micro-scale biodigester failures are a result of either lack of technical skills or the knowledge of the biodigestion process. For digesters to operate successfully and vigorously, microorganisms need to be kept alive at all times. Guarantying a healthy state of microorganism is above all depended on the category and amount of organic material fed into the digester, feeding frequency, the temperature a digester operates at, the availability of water (this is often a challenge is remote rural areas in South Africa). Lastly, ensuring that the pH of the digester is maintained at an acceptable range also contributes to digester failure (GIZ, 2016). Failure to optimise and carefully manage digester parameters will be discussed later.

The greater part of micro-scale biodigester beneficiaries does not have the required skills for digester maintenance nor the knowledge that could prevent biodigester breakdown. The GIZ (2016) study found that a significant portion of biodigester projects installed in schools had champions who are attentive to the wellbeing of a digester. These champions value the benefits provided by a digester in the school feeding scheme program (i.e. cooking gas and bio-fertiliser). Furthermore, the digestate by-product that they use as a fertilizer for gardening is appreciated by biodigester users. Digester failure in schools can therefore not be attributed to the lack of operator involvement but to a certain extent, lack of technical skills (GIZ, 2016). It is important to understand that skilled builders are a prerequisite for avoiding failures associated with improperly conducted construction (Banout *et al.*, 2016).

### 4.1.2 Human error implications

Digester feeding is primarily dependent on human beings. GIZ (2016) accentuates that inappropriate feeding is another reason for digester breakdown. McCarty (1964) gives details about the importance of ensuring that microorganism does not die. If a digester is not fed correctly or not fed at all for whatever reason, the microorganisms will die. Once microorganisms die, the digester can no longer generate biogas, consequently, it stops working (McCarty, 1964). Mensah & Forster (2003) explain that feeding detergents such as non-biological liquid, washing ingredients and fabric softeners can lead to a digester failure as well as the eradication of microorganisms. Digester failure related to the death of microorganism, as a result of inappropriate feeding, is regarded as a biological failure (GIZ 2016). For this reason, human-influenced error and biological failure have a strong correlation. Nearly 22% of digesters installed before 2014 are still operational in the Eastern Cape (GIZ, 2016). The identified common cause associated with a high degree of digester failure is biological, however, this is related to the human-influenced error. Usually, human-influenced error indirectly triggers a biological failure, therefore, a large degree of digester failure can be weighed towards human-influenced error. The person responsible for operating the digester has a responsibility of ensuring that the digester is operated in a sustainable manner, this also refers to paying attention to various parameters involved in a digester. Biodigester breakdown is a consequence of mismanagement, committed by the person responsible for operating the digester. A continuous success of a digester is dependent on the individual tasked with the duty of operating the digester. It is worth mentioning that in circumstance were human error was found to be responsible for digester failure, lack of interest and eagerness from beneficiaries were identified as underlying factors (GIZ, 2016).

### 4.1.3 Lack of digester operational training

According to Mukumba *et al*. (2016a), government, non-governmental organisations, and biogas installers should provide adequate training to biodigester end-user on how to feed and maintain digesters. Anaerobic digestion refers to live microorganisms that survive from being fed with biomaterial in the absence of oxygen (GIZ, 2015). This process requires a certain level of knowledge from those who are in charge of the operating biodigesters, and it will guarantee that digesters remain alive and healthy in a long-run. According to GIZ (2016), it is critical to provide appropriate initial training to the beneficiaries and specifically the future operators to ensure that they are left with enough knowledge to operate digesters with confidence in the long term. If this rationale is compared with the precedence that the electricity supply sets in South Africa, where the responsibility of operating the electricity supply, infrastructure maintenance and other parameters is a legal responsibility of the national utility (Eskom). It can then be argued that biodigesters installers have expertise in the entire biological process of anaerobic digestion. Therefore, it is only logical to make the biodigester infrastructure and maintenance the responsibility of biodigester installers. The GIZ (2016) study identified one possible cause for biodigester failure as a lack of “initial training”, however, it is the author’s view that lack of financial support for maintaining digesters was the main cause of digester failure in the Eastern Cape. Furthermore, it is the author’s view that the training recommended by GIZ (2016) for operating biodigesters is detrimental to the biodigester success rate. Lastly, the author's experience in working with micro-scale digesters has shown that biodigester beneficiaries are mainly interested in the energy output that they gain from having a biodigester.

In some of the digesters that the GIZ (2016) study covers, there were damaged components, which included among others, damaged balloon digester storage bag, gas flow meter or a gas extraction pipe as shown in Figure 14.

**Figure 14: Balloon digester bag in Melani village (Eastern Cape & gas flow meter** ***Source: GIZ (2016).***

Biodigester beneficiaries indicated that they did not receive any formal training, other than being taken through basic operational rules after construction was concluded. The study states that it is relatively straightforward to operate a biodigester, on conditions that, operational rules are strictly adhered to (GIZ, 2016). However, factors of public health that Cote *et al*. (2006) point to in terms of pathogen reduction as one of the objectives for a biodigester, are not considered by the GIZ (2016). Mihelcic *et al*. (2009) emphasize that pathogens instigate public health risk through diarrhoea infections that are so common in rural areas as a result of poor hygiene and a lack of better water and sanitation services. The GIZ study does not take into account the health conditions of those that should be responsible for feeding a biodigester. There are no guidelines provided except underscoring that feeding a digester is straightforward. Beneficiaries that might be suffering from lung infections such as tuberculosis (TB) are not considered in this regard. Taking into account the health risk triggered by pathogens, capacitating biodigester beneficiaries to be able to feed and operate a digester is unpleasant therefore unattractive. Health conditions of potential biodigester operators should be the primary factor considered before biodigester operational training.

GIZ (2016) further indicates that biodigester operational challenge is triggered when an error is beyond basic straightforward operational procedure. Diagnosing the cause of digester failure is far complicated than the recommended straightforward initial training stated by (GIZ, 2016). As a result, it can be concluded that ordinary beneficiaries of digesters are not equipped to operate biodigesters. Furthermore, the 65% overall failure found in the Eastern Cape case study is mainly attributed to assigning biodigester maintenance responsibility to digester end users. The detrimental findings by GIZ (2016) that 78% of micro-scale biodigesters installed in between 2010 and 2014 are no longer operational raises concerns. Undoubtedly, the initial training offered is not effective, therefore, considered incompatible and inappropriate.

### 4.1.4 Appliance and mechanical failure

Uncommonly, the GIZ (2016) study only found one biodigester that broke-down as a result of what could be categorized as a mechanical failure. The digester installed at Mbawule School (Eastern Cape) was found to be configured correctly, however, the school suspended feeding because the gas abstraction pipe was damaged. Other identified biodigester mechanical failures were attributed to blocked pipes, digester protection, gas and liquid leaks. During the reconstruction that took place at Mbawule school, some of the biodigester parts that were uninstalled were never reinstalled (GIZ, 2016). According to Banout *et al.* (2016), the most common challenge with structural components in the biodigester are related to the inlet pipe, this is consistent with the finding by (GIZ, 2016).

Another identified problem with digesters is the inconvenient location which leads to accessibility challenges. Badly constructed of biodigesters is another challenged that associated with low-quality workmanship (Banout *et al.*, 2016).

**Figure 15: Ballon bag digester damaged in Cedarville (Kwazulu Natal)**
***Source: (GIZ, 2016).***

The biogas storage bag illustrated in Figure 15 was found putrefied at Cedarville High School. The damage was found to be associated with improper biodigester installation. Currently, there is no accredited biogas installers nor micro-scale biodigester installation regulations or a policy framework that regulates biodigester installations in South Africa. The Three Crowns High School biodigester illustrated in Figure 16 encountered primarily mechanical problems, specifically, seized gears on the paddle wheels of the algae ponds (GIZ, 2016).

**Figure 16: Three Crowns High School Algae pond**
***Source: GIZ (2016).***

According to GIZ (2016), the common cause of biodigester failure is associated with lack of maintenance. The findings indicated that most of the biodigester breakdown could have been prevented if beneficiaries were constantly receiving technical support from biogas experts. Moreover, access to financial support or necessary funds for experts to implement guidance and digester maintenance would have resolved the higher digester failure rate. The three Crowns School biodigester has not been functional for some time and reasons for shelving in this regard was a result of a drought. Lack of water supply exclusively rendered the digester non-functional (GIZ, 2016).

### 4.1.5 Lack of financial support

Inadequate funding is somehow linked to insufficient support given to digester beneficiaries. The contractors that install digesters do not have the budget for maintaining biodigesters beyond the installation and commissioning phase. This is the principal problem with most installed biodigesters. Micro-scale digesters installed in South Africa are generally donor-funded and limited resources from donors leave communities without funding for maintenance. GIZ (2016) found that in some circumstances, contractors provide technical support at their own cost to build a good reputation for themselves with the hope that they will have an opportunity to install more biodigesters in the future. The GIZ (2016) recommended that an installation contract should be packaged in a way that ensures digesters run smoothly. Contrarily, installed digesters covered in the GIZ (2016) study were installed and commissioned by contractors who never factored in maintenance cost in the extortionate price they charge (See Appendix: F). Most of these projects are located in isolated parts and remote areas thus making it more complex and costly to initiate site visits. Subsequently, biodigesters are left with no one given responsibility in terms of maintenance. GIZ (2016) concluded that lack of funding played a major role in the high digester failure rate encountered in the Eastern Cape. The author is of the view that these failures are attributed to lack of digester policy rather than a lack of funding. If there was a policy that will obligate biodigesters donors and contractors, to maintain installed digesters over the lifespan of a digester, the high failure rate could be decreased. Tucho *et al.* (2016) identified the financial capacity of the people, the technical capacity to maintain the system, and socio-cultural barriers preventing people from using the digesters in a sustainable manner.

### 4.1.6 Proposed community involvement process and beneficiary selection in rural areas

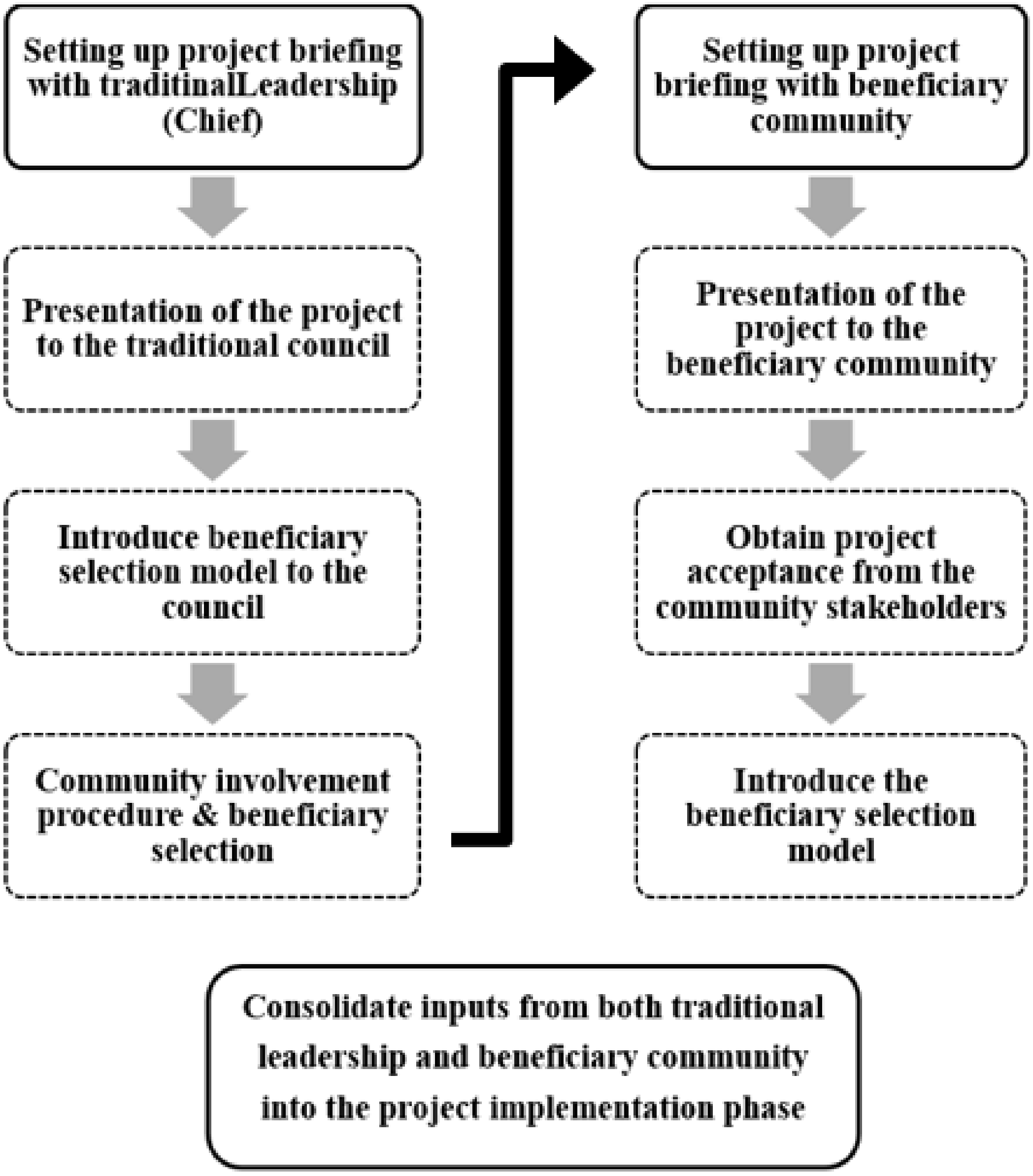



**Figure 17: Stakeholder involvement process**

The ultimate success of a digester is depended on community or human involvement. GIZ (2016) identifies that without a responsible person assigned to look after a digester on daily basis, the likelihood of biodigester surviving is minimal. A crucial component of a successful implementation of a biodigester project is appointing a responsible person. In circumstances where the biodigester beneficiary "champion" leaves a community for better opportunities in urban areas, the digester would fail, thus this recommendation might be unfavourable. Community members should be fully informed about what would be expected of them if they were to be beneficiaries of the biodigesters. One micro-scale biogas digester identified as part of this study is the Indwe Project funded by the Water Research Council (WRC). This project followed an all-inclusive community involvement process in depth with elaborate and extensive community consultation. It is important to indicate that regardless of the robust biodigester model implemented by the WRC, only one out of five biodigesters installed is still operating (GIZ, 2016). Evidently, the WRC biodigester implementation model has weaknesses as well hence the success rate of 20% is recorded.

#### 4.1.7 The proposed approach for prolonging micro-scale biodigester lifespan

The lifespan of a micro-scale digester is affected by five points discussed in section 4.1.1 – 4.1.5, as a result, a technique for prolonging a digester lifespan is proposed.

**Lack of technical skills** – A micro-scale biodigester operational guide for end users need to be developed. This will assist digester users to understand how to feed, how often they should feed and the material that needs to be fed. The proposed operational guide should also include a basic capacity building on how microorganisms perform in a digestion process.

**Human error** – The proposed solution for minimising human error implication is to equip end users with knowledge on what will happen to microorganisms in situations where they fail to feed the digester. This will assist end users to understand how biogas is generated and thus be able to detect possible causes for digester failure. The capacity building should mainly inform digester users about the HRT process, causes for microorganism death and inappropriate feeding that lead to biological digester problems.

**Lack of digester operational training** – The training provided for digester users is ineffective since it is done over a short period. Ensuring that a digester stays in a flourishing condition requires constant digester care. The proposed solution in this regard is to ensure that all micro-scale biodigesters are operated by certified digester operators who have been well trained in an anaerobic digestion process and parameter optimisation.

**Appliance and mechanical failure** – The proposed solution for appliance and mechanical failure is to ensure that all digesters that are installed have a maintenance budget that will be utilised for replacing spares when necessary. This will enhance the lifespan of a micro-scale biodigester and it correlates with the proposed sustainable operation method for a micro-scale biodigester discussed in section 4.4.3.

**Lack of financial support** – The proposed solution for availing funds that will support the adoption of micro-scale digester is through establishing a clean energy fund for rural communities. This fund needs to be provided by the Department of Energy (DoE) under the INEP that is mandated to promote equal access to basic energy services for all South Africans, including electrifying households located in deep rural areas where installation cost is much higher. Digester end users should make a financial contribution towards operations and maintenance. This approach will lessen the maintenance problems and promote biodigester sustainability.

### 4.2 Revision of Bio-gas production process

According to Rowse (2011), there are six basic user input variables for a biodigester design. The model developed in this regard is demonstrated in Table 9 (Rowse, 2011). The user kit includes the following basics tools:

- Type of animals
- Number of livestock
- Average of summertime temperature
- Average of wintertime temperature
- Digester type
- Animal preparation

The archetypal design depicted in Table 9 utilises the theory of "mass balance and reaction rate kinetics" for quantifying dimension, size and gas storage of the reactor basin (Rowse, 2011). The volumes of water used in a single digester daily determine the amount of biogas needed per household per day.

**Table 9: Six user inputs for a biodigester design**

***Source: (Rowse, 2011).***

**Average of the warmer period and the temperature**

**Average of winter period and the temperature**

| | |
|---|---|
| 1) Type of animals | Beef cattle |
| | Dairy cow |
| | Poultry |
| | Piggery gestating sow |

| | |
|---|---|
| | Wild boar piggery |
| 2) The number of animals feeding a digester | |
| 3) Average warm season temperature | |
| 4) Average cold season temperature | |
| 5) Reactor design type | Fixed Dome |
| | Floating-drum |
| | Polyethene tubular |
| 6) Preparations for feeding animals | Animals are free during the day, locked up at night-time. |
| | Animals are free going biannually, confined biannually. |
| | Animals are confined throughout the year. |

Rowse (2011) highlights six significant input factors that need to be taken into account when an anaerobic digester is operated. These imperative factors are discussed intensely in the section (4.2.1 – 4.2.13).

### 4.2.1 Stoichiometric Coefficients with the R Equation

One of the significant feature of anaerobic digestion is stoichiometry (Rowse, 2011). Mass and charge are always preserved as illustrated by Rittmann & McCarty (2001). Rittmann & McCarty (2001) concluded that safeguarding mass is of paramount importance. This is accomplished by means of mass balancing. As a result, the intermediary results such as carbon, nitrogen, hydrogen, oxygen and other gas components that manifest prior to methane generation can be reported. Protection of the charge is confirmed by means of harmonizing "electron comparisons in the oxidation-reduction reaction pairs" (Rittmann & McCarty, 2001). Most electrons similarities (chemical and physical properties of methane) fed into the reactor as Biochemical Oxygen Demand (BOD) load are preserved through reducing the amount of carbon to its minimum by means of a redox reaction process until the methane gas is negative four (-4). This technique exterminates BOD as a liquid form through transforming electrons similarities to methane gas. Post this phase, the removal of BOD and waste stabilization is dependent on methane formation (Rittmann & McCarty, 2001).

The final output of methanogenesis (the formation of methane by microbes) contains methane, carbon dioxide, biomass and water. One percent of electrons similarities, *f*s, synthesize into biomass while the remaining electrons similarities, *f*e, converts into energy. Methane is produced by anaerobic digestion in two forms, firstly, through the oxidation of hydrogen, secondly, by means of splitting acetic acids. Carbon dioxide accepts electrons in the oxidation of hydrogen to generate methane gas. In the context of stoichiometric reactions, splitting acetic acids are also believed to accept electrons as shown in equation 4.2.2. The R equation is represented through the electron acceptor ($CO_2$) the electron supporter (the biological waste particles) and cell synthesis which is quantified through the CHON molecular method (Rittmann & McCarty, 2001). The "organic reaction" for calculating biological particles is represented by $C_nH_aO_bN_c$ – defined as:

$$R_d = \frac{c}{d} NH_4^+ + \frac{c}{d} HCO_3^- + \frac{(n-c)}{d} CO_2 + H^+ + e^- = \frac{1}{d} C_nH_aO_bN_c + \frac{(2n-b+c)}{d} H_2O \qquad \textbf{(4.2.1)}$$

Where $R_d$ = electron donor half-reaction

$d = (4n + a - 2b - 3c)$.

Electron accepted by carbon dioxide in the anaerobic digestion process is referred to as the "electron acceptor half-reaction" (Rowse, 2011) represent by:

$$R_a = \frac{1}{8} CO_2 + H^+ + e^- = \frac{1}{8} CH_4 + \frac{1}{4} H_2O \qquad \textbf{(4.2.2)}$$

Where $R_a$ = electron acceptor half-reaction.

The "cell synthesis half-reaction" amongst ammonium as the nitrogen source (Rowse, 2011) represented by:

$$R_c = \frac{1}{5} CO_2 + \frac{1}{20} HCO_3^- + \frac{1}{20} NH_4^+ + H^+ + e^- = \frac{1}{20} C_5H_7O_2N + \frac{9}{20} H_2O \qquad \textbf{(4.2.3)}$$

Where $R_c$ = cell synthesis half-reaction.

Generally, Rittmann & McCarty (2001) defines the R equation as:

$R = f_e Ra + f_s R_c - R_d$

R represents = the R equation

$f_e$ = fragment of energy saved through waste balancing.

$f_s$ = fragment of the energy that is directed to the cell synthesis.

The $f_e$ is estimated to be = 0.92 (Rowse, 2011).

According to Lee *et al*. (2008), it can be concluded that piggery dung is bio-degradable at 65.6%. The bio-degradable percentage is dependent on a number of factors such as the Solid Retention Rate (SRT), temperature and the type of feedstock. The methodology developed by Lee *et al*. (2008) standardises feedstock to be degradable at 65.6%. "The COD for each animal waste was multiplied by 65.6%, and the subsequent degradable fraction of the waste stream was used instead of the COD in calculating the CHON formula for the waste stream".

### 4.2.2 Hydraulic Retention Time (HRT), and Solids Retention Time (SRT)

Hydraulic retention time, **Đ** (days), represents an average amount of time one reactor actively digests sludge loaded into it. The numeric definition is as follows:

$$\text{Đ} = \frac{V}{Q} \qquad \textbf{(4.2.4)}$$

Where: **Đ** = HRT (d)

V = volume of reactor ($m^3$)

Q = effluent flow rate (Rowse, 2011).

HRT is a significant parameter for the digestion operation and design since it characterizes the duration the feeds and specific components meant to decay will be in contact with the biomaterial inside the reactor (Rowse, 2011). According to Khanal (2009), the rate-limiting in an anaerobic digester is the reaction kinetics of methanogenesis and fermentation process. According to Garfi *et al.* (2011), experimenting using psychrophilic digesters under different temperature conditions gives an SRT guideline. Garfi *et al*. (2011) experiment indicate that at the temperature of 10°C, an SRT of 70 days is recommended for polyethene digester without mixing. For temperatures near 30°C, an SRT of 20 – 30 days is regarded as sufficient (Garfi *et* *al*., 2011). Reactor designs should always correspond with retention times, this is to allow volatile solids to decay appropriately (Rowse, 2011).

### 4.2.3 Solid Retention Time

Solids Retention Time (SRT) represents organisms setting in a biodigester separated by the form of organisms detached from biodigester processing on daily basis (Rittmann & McCarty, 2001). The numeric definition of solids retention time is as follows:

$$\theta c = \frac{\text{Active biomass in system}}{\text{Production rate of active biomass}} = \frac{V * X}{Q_w * X_w} \quad \textbf{(4.2.5)}$$

Where $\theta c$ = Solids retention time (d)

V = reactor volume ($m^3$)

X = cell concentration in reactor

$Q_w$ = flow rate out of the reactor

$X_w$ = cell concentration in the flow out of the reactor

SRT is of paramount importance since it has a potential to washout organism, this can only materialise if the SRT is low (Rowse, 2011). If the SRT can prolong, the system produces limited nutrient, therefore, the SRT shock in the organisms modifies the microbial ecology of the system as a result of optimal enlargement of solids (Rowse, 2011). Vesilind (1998) identifies an SRT to be equal to HRT in the absence of solids recycle. Maximising the SRT increases the anaerobic digestion. Lengthy SRTs sustains the digestion process, reduces the sludge produced and optimises biogas generation (Rowse, 2011). Rittmann & McCarty (2001) indicates that the minimum number of days a SRT concludes treating waste is 10 days at a temperature of 35 ºC, known as Continuous Stirred Tank Reactor (CSTR).

### 4.2.4 Organic Loading Rate (OLR)

According to Vesilind (1998), an OLR represents aggregated volatile solids conveyed to a digester on daily basis. According to Tchobanoglous *et al*. (2003), OLR also represents the amount of Biological Oxygen Demand (BOD) or Carbonaceous Oxygen Demand (COD) functional inside the reactor. The OLR correlates with the HRT through the following equation:

$$OLR = \frac{(Q)(C_{vs})}{V_{reactor}} = \frac{C_{vs}}{HRT} \qquad \textbf{(4.2.6)}$$

OLR represent the = Organic loading rate

Q = volumetric flow rate ($m^3/d$)

$C_{VS}$ = concentration volatile solids (kg VS/$m^3$)

Vreactor = reactor volume ($m^3$)

HRT = hydraulic retention time.

If recycling is nonexistence, SRT = HRT, this is represented through the following equation:

$$OLR = \frac{C_{VS}}{SRT} \qquad \textbf{(4.2.7)}$$

According to Rowse (2011), the active biomass absorption, cell fragments subsequent decomposition and non-biodegradable unstable material represent Volatile Solids (VS). Rittmann & McCarty (2001) recommends an OLR of 1.6 – 4.8 kg VS/($m^3$*d) for high-rate anaerobic digestion. Speece (1996) recommends an OLR of 5 – 10 kg VS/($m^3$*d) though Vesilind (1998) recommends a peak OLR of 1.9 – 2.5 kg VS/($m^3$*d) for high-rate anaerobic digestion. Sharma & Pellizzi (1991) recommends an OLR of 1.0 – 3.5 kg VS($m^3$*d) for standard-rate anaerobic digesters.

Rowse (2011) describes that if anaerobic digester loading rate is excessively high for digester setting, there is a possibility for the two methanogenesis to be withdrawn. This could stimulate an accumulative digester Volatile Fatty Acids (VFA). The existence of VFA reduces the pH in the digester vessel, thus intensifying the presence of the acid (Rowse, 2011). Rowse (2011) further explains that an increased acid in the reactor is highly likely to cause a digester failure, as a result, it is essential to ensure that the OLR is conservative. Increased acid causes drops in pH, hence it reduces methane generation.

#### 4.2.5 Safety Factor

Large-scale Wastewater Treatment Plants (WWTP) digester vessels are intentionally modelled to have tough safety factors for a number of motives; these rationales include among others, the poor operational monitoring tools, inconsistencies in WWTP watercourse and other variations in operational surroundings (Rowse, 2011). Rowse (2011) signifies that the Biomaterial treatment systems have different safety factors relative to other infrastructure. This is pointed out through the minimum SRT for volumes of the bacteria that is contained in a micro-scale reactor. This can then form the basis for the cell destruction in the digester overflow, known as digester washout (Rowse, 2011). In circumstances where the washout transpires, the safety factor is multiplied by the SRT (Rowse, 2011). If the SRT is too low there will a microorganism washout, therefore, it is important to have a large safety factor. Exclusively, in rural dwellings, there is high volatility in the ambient temperature, variation in the substrate manure feedstock in diverse seasons, limited operator supervision, lack of technical expertise and process control. Finally, if the anaerobic digester stops working, it certainly has a negative consequence for the development of the micro-scale biodigesters which are commonly used in rural areas. The ripple effects of such failures range from loss of faith in the biogas technology to blockages of future micro-scale biodigesters development. Rittmann & McCarthy (2001) recommends a safety factor of 10 – 30 as indicated in Table 10. This means that pressure in the reactor must be less than the bearing capacity of a digester. Table 10: Recommended digester operational parameters

| Sources | Operating Parameters | Parameter values |
|---|---|---|
| (Sharma & Pellizzi 1991) | OLR [kgf VS/(d*m$^3$)] | 1.0 - 3.5 |
| (Tchobanoglous *et al*., 2003) | SRT $^{min}_{lim}$ (d) | 4 |
| (Garfi *et al*., 2011). | SRT (d) | 20 - 70 |
| (Rittmann & McCarthy, 2001) | pH & Safety Factor (SF) | 6.6 - 7.6 & 10 - 30 |

#### 4.2.6 Mixing

Mixing is one vital parameter important when designing an anaerobic digester since it stimulates the reaction kinetics of anaerobic digestion, thus stepping up the biological conversion modus operandi (Tchobanoglous et al., 2003). Mixing for both floating drum and fixed dome micro-scale reactors usually happen during feeding application, where manure or any organic material is mixed with water just before it is fed into the digester. An additional mixing for digesters transpires once gas is formulated in the digesting slurry layer. This fills up the digester with gas while it creates a hovering or floating for a floating system (Tchobanoglous et al., 2003). According to Tchobanoglous et al., (2003) mixing can also be implemented automatically via an electronic mechanism that can infuse methane and carbon dioxide gases into the reactor, this can be loaded through spargers and electronic gas flushers joined at the lowermost of the biodigester. In best conditions, the Plug Flow Reactor (PFR) within the digester normally has a consistent concentration of microorganisms and substrates. For this process to be realised, no mixing should occur with earlier or later entering flows (Rowse, 2011).

### 4.2.7 pH


**Figure 18: Digital pH meter**

***Source: (Mukumba et al., 2016b).***

The pH computing device illustrated in Figure 18 is one of the most vital instruments for parameters monitoring in the anaerobic digestion process. Rittmann & McCarthy (2001) emphasizes that the pH should be sustained between 6.6 and 7.6. Immediately after the feeding commences for a newly completed digester, overloading and volatility results in organic acids yield created in-between by the microorganism. High absorption of macrobiotic acids reduces the pH and methane generation, thus triggering a reactor malfunction (Rittmann & McCarthy, 2001). According to Rowse (2011), carbonic acids organism manages the pH control in the largest part of anaerobic digestion. In addition, carbon dioxide balancing is an important factor in anaerobic digestion, subsequent to computing the reliance and stability of pH in bicarbonate alkalinity (pointed out in subsection 4.2.8). Rittmann & McCarty (2001) explain that pH in the biodigester is dependent on bicarbonate alkalinity integration for both the carbon dioxide and liquid gas.

#### 4.2.8 Alkalinity

According to Rittmann & McCarty (2001), alkalinity is the ability of water to neutralise acid contained in the digester. Gas composition of carbon dioxide in a biodigester ranges between 25 and 45% (Rittmann & McCarty 2001). In circumstances where the carbonate system is widespread, the subsequent proton balancing is relevant

$$[H^+] + [Alkalinity] = [HCO_3^-] + 2\,[CO_3^{2-}] + [OH^-] \qquad (4.2.8)$$

The assessment of leftover species, hydroxide, hydrogen and carbonate existing at hand has insignificant concentration. Lastly, the logarithm of both parts condensed is represented by connecting pH, bicarbonate alkalinity and the percentage of carbon dioxide, exemplified by the following equation:

$$pH = pK_{a_1} + \log\left(\frac{\frac{Alk.(bicarb.)}{50000}}{\frac{[CO2(g)]}{KH}}\right) \qquad (4.2.9)$$

A minimum of 500 – 900mg/L CaCO3 is required in bicarbonate alkalinity for a pH greater than 6.5. Adding alkaline substance in the absence of carbonate buffering in wastewater sustains the pH within the acceptable range for anaerobic digestion (Rittmann & McCarty, 2001). The three cheapest chemicals that could be added to strengthen alkalinity are lime, sodium hydroxide and ammonia (Rowse, 2011). Finally, knowing the pH and carbonate illustrated by the pH equation ensures that the pressure of the carbon dioxide is quantifiable; this is vital for understanding and monitoring the biodigester behaviour (Rittmann & McCarty, 2001).

#### 4.2.9 Temperature

The microorganism development intercedes via an intricate set of chemical biodegradation conduct while the conduct percentage of all substance behaviour in a biodigester process is dependent on temperature including the microorganism growth. The common rule is that for every 10°C increase in temperature, the microorganism grows in twofold for various bacterial species. Rittmann & McCarty (2001) describes that higher temperatures for specific microorganism species may result in permanent loss of crucial enzymes. Mesophilic bio-digestion operates at a temperature ranging between 10° and 45°C (Haig & Gorgens, 2013; Rittmann & McCarty, 2001). Over 45°C, essential enzyme denaturalization is an alarming factor, however, the thermophilic anaerobic digestion operates between 50 and 65°C (Haig & Gorgens, 2013; Rittmann & McCarty, 2001). For thermophilic anaerobic digestion, methane generation is 50 – 100% higher than the mesophilic (Rittmann & McCarty, 2001).

#### 4.2.10 Oxygen

According to FNR (2012), methanogenic archaea are categorised as one of the oldest existing microorganism. They were first discovered approximately three to four billion years ago, that was prior to the formation of the atmosphere. At present, bacteria presence is dependent on an environment deprived of oxygen, numerous groups of organisms are destroyed by insignificant amounts of oxygen. In general, it is impossible to totally avert oxygen present in a biodigester. Methanogens coexist with oxygen-consuming microorganisms from the early stages of degradation. A few of the microorganisms are known to be facultative anaerobic bacteria, these bacteria types are strong enough to coexist in the presence of oxygen as well as without any existence of oxygen. In circumstances where the level of oxygen to not too high, bacterium consumes oxygen before it can destroy the methanogenic archaea. Therefore, the minimal oxygen added to the gas space removes sulphur generated during the digestion process (FNR, 2012).

#### 4.2.11 Nutrient resources

FNR (2012) clarify that the microorganisms encompassed in anaerobic digestion have specific macronutrients and vitamin requirements. The amount of nutrients determines the bacteria growth rate and the behaviour of various populations in a digester. The concentration levels in the digestion process regulate the least and the most amount of methane that could be generated. In order to secure maximum methane generation from feedstocks, optimum supply of nutrients to the bacteria must be accurate. These dynamics determine the number of nutrients required. It is therefore important to stabilise the amount of carbohydrates, protein, and fat homogenises determine the methane that could be produced from various feedstocks. In ranking the digestion requirements, after carbon and nitrogen, nutrients are the most vital components needed. Nutrients are needed to ensure that enzymes are formed for performing metabolism. Inadequate metabolism may result in the poor conversion of the amount of carbon available from substrates degrading, thus affecting the maximum yield methane production. Excessive nitrogen produces ammonia ($NH_3$) which should be between 0.1 and 0.5%. This can then lead to low concentration levels of methane generation due to low volumes of nutrients needed in a digestion process (FNR, 2012).

### 4.2.12 Volatile Solids Reduction

For measuring the concentration of carbonate alkalinities and VFA, Lahav & Morgan (2004) assessment concluded that programmed software titration equipment is appropriate and ideal for electronically monitoring of anaerobic digesters in developing countries.

### 4.2.13 Automated digester parameter monitoring

Monitoring bio-digestion models is an important factor that will ensure that micro-scale digester designs are robust and sustainable. According to Rowse (2011), a large number of operational biodigesters are operated with no monitoring. Figure 19 shows some of the parameters that need to be monitored in a micro-scale biodigester. This means that accurate data and the root cause for digester failure will always be limited until all these parameters are studied attentively. Even so, more often than not, if a biodigester parameter monitoring study is conducted, the parameters that are usually monitored are basic parameters visible from the outside.

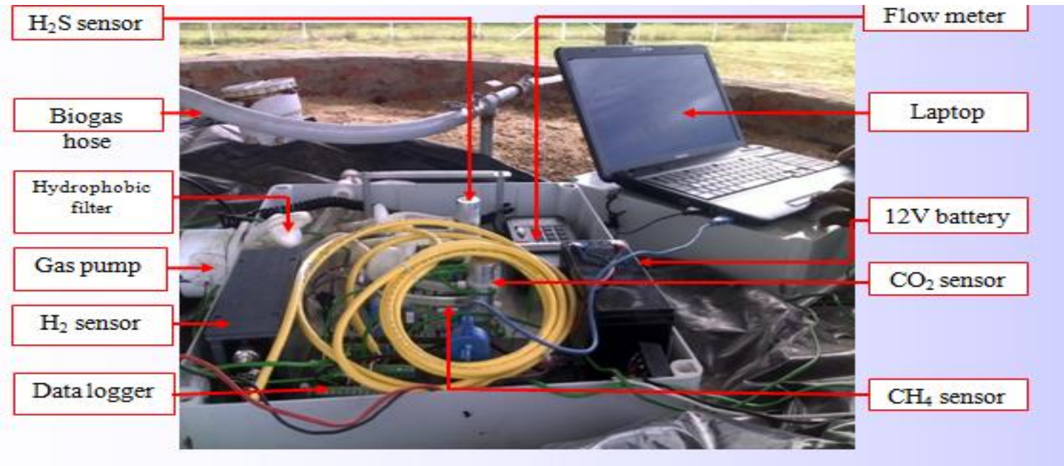



**Figure 19: Biodigester parameter monitoring**

***Source: (Mukumba et al., 2016b)***

Furthermore, digesters operated in South Africa are often confronted with technical operational challenges. Rowse (2011) recommends monitoring as a possible solution to improve the longevity of a biodigester. Monitoring, sampling techniques and safeguarding of the reactor parameters are detailed in Table 11. Eaton *et al*., (2005) indicate that comprehensive monitoring of all the parameters shown in Table 11 can improve the lifespan of a biodigester, this is indicated by (Hach, 2011) as well. The all-inclusive parameter monitoring is significant in situations where transporting samples from rural areas to relevant laboratories and cooperation laboratory for analysis is difficult. Rowse (2011) emphasizes that this may take a very long time and further recommends ice-cold mechanisms as an alternative method for storing samples at a low temperature.

**Table 11: Biodigester parameter monitoring**

***Source: (Rowse, 2011; Hach 2011).***

| Parameter to Monitor | Method | Field Application |
|---|---|---|
| Manure Loading Rate | Volume, Mass | The container of a known amount |
| Water loading rate | Amount | The container of a known amount |
| Gas Generation | Gas Examiner | Gas Examiner |
| Gas Configuration | Standard Method 2720 B | Partner lab |
| | Standard Method 2720 C | Partner lab |
| Total Solids, Volatile Solids | Normal Process 2540 B, and 2540 E | Laboratory |
| OLR | Compute daily volatile Solids | |
| Conductivity Partner lab | Normal Process 2510 B | N/A |
| pH | Normal Process 4500-$H^+$ | Laboratory |
| Alkalinity | Normal Process 2320 B | Laboratory |
| Temperature | Thermometer | Thermometer |
| Ammonia ($NH_3$) | Normal Process 4500-$NH_3$.F | Laboratory |
| Total Nitrogen | Normal Process 4500-P J. | Laboratory |
| | Hach Process 10071 | Fieldwork |
| Total Phosphorus | Normal Process 4500-P J. | Laboratory |
| | Hach Process 8190 | Fieldwork |
| COD | Normal Process 5220 D | Laboratory |
| | Hach Process 8000 | Fieldwork |

| | | |
|---|---|---|
| BOD | Normal Process 5210 B, Normal Process 4500-O G | Laboratory |
| | Liquefied oxygen probe and meter | Laboratory |
| TOC | SM 5310 B | Laboratory |
| HRT | Compute Volume/Flowrate | The container of a known amount |
| SRT plate | Measure Flowrate of slurry out, Normal Process 2540 B (TS) | Container of known amount, TS=Laboratory |

## 4.3 Gas production mechanism

### 4.3.1 Gas production analysis

Hermann Sewerin GmbH SR2-DO portable gas examiner is an instrumental tool for analysing gas compositions contained in anaerobic digestion (Aklaku *et al*., 2006). Analysis conducted utilizing a Hermann Sewerin GmbH SR2-DO indicated non-existent of ammonia while the fraction of hydrogen sulphide gas was 0.002%. Aklaku *et al*. (2006) also calculated the amount of carbon dioxide gas contained in biogas, this was calculated through measuring the percentage of $CO_2$ in methane enclosed in the mixture since the hydrogen sulphide gas found was insignificant, this calculation was done through the following representation:

$$\mathbf{CH_4 = 100 - CO_2} \qquad \textbf{(4.3.1)}$$

Rowse (2011) elucidates that the volume of biogas generated per day is dependent on the amount of manure collected. This is reachable through livestock arrangements, free moving animals during the day and confined at night offers only 50% of manure (Rowse, 2011). If all livestock were kept in a shed area, manure collection would be assumed to be at 100%, however, given that this is not the case, a concentrated manure collection is feasible at a 50% ratio (Rowse, 2011). The volume of biogas produced daily is measured by determining the mass of volatile solids (VS) fed into biodigester daily (Rowse, 2011).

$$\text{mass VS} = \text{Volatile Solids} \qquad \textbf{(4.3.2)}$$

$(mass\ VS)_{swine\ boar}$*$(no.\ animal)_{swine\ boar}$ + $(mass\ VS)_{swine\ sow}$ *$(no.\ animal)_{swine\ sow}$ +

$(mass\ VS)_{poultry}$*$(no.\ animal)_{poultry}$ + $(mass\ VS)_{beef\ cattle}$*$(no.\ animal)_{beef\ cattle}$ +

$(mass\ VS)_{dairy\ cattle}$*$(no.\ animal)_{dairy\ cattle}$

Where mass VS =

total mass VS loaded per day (kg VS/($m^3$*d)) **(4.3.3)**

The number of moles of the organic molecule, CnHaObNc, added to the reactor per day (mol CnHaObNc/d) is calculated through:

$$\frac{mass\ VS\left(\frac{kgVS}{d}\right)*1000}{MW} = mol\ C_nH_aO_bN_c/d \qquad \textbf{(4.3.4)}$$

Where MW = molecular weight of $C_nH_aO_bN_c$ (g)

Methane generation daily is calculated through:

r (mol CH4/d) = x (mol $C_nH_aO_bN_{c/d}$) * M/C **(4.3.5)**

Mass VS = mass VS added per day (kg VS/d).

Where r = number of moles of methane per day, (mol CH4/d)

x = number of moles of CnHaObNc per day, (mol CnHaObNc /d)

M = coefficient of methane in the overall R equation

C = coefficient of CnHaObNc in the overall R equation.

Number of moles of carbon dioxide produced per day was calculated through:

m (mol $CO_2$/d) = x (mol $C_nH_aO_bN_{c/d}$) * B/C **(4.3.6)**

Where m = number of moles of carbon dioxide per day, (mol CO2/d)

x = number of moles of CnHaObNc per day, (mol CnHaObNc /d)

B = coefficient of carbon dioxide in the overall R equation

C = coefficient of CnHaObNc in the overall R equation.

$$V = (n*R*T)/P \quad \textbf{(4.3.7)}$$

Where V = volume of biogas produced per day ($m^3$ biogas/d)

n = total number of moles of biogas generated per day; n = r + m (number of moles biogas/d)

R = gas constant = 8.3144 J/(mol*K) = ($m^3$*Pa)/(mol*K)

T = temperature (K)

P = total pressure of system (Pa).

### 4.3.2 The percentage of methane composition

The percent methane (wt.%) in the biogas is calculated through:

$$\text{methane wt.\%} = \frac{\text{r (mol CH4/d)}}{\text{r}\left(\text{mol}\frac{\text{CH4}}{\text{d}}\right)+\text{m}\left(\text{mol}\frac{\text{CO2}}{\text{d}}\right)}*100 \quad \textbf{(4.3.8)}$$

Where methane wt.% = percent methane in the biogas

r = number of moles of $CH_4$ produced per day (mol $CH_4$/d)

m = number of moles of $CO_2$ produced per day (mol $CO_2$/d).

### 4.3.3 Amount of water utilised per day and the size of digester

Rowse (2011) demonstrate that the accumulated manure generated daily is measured as a weighted average of manure mass values indicated in Table 12. The various feeds indicated in Table 12 are used to quantify gas yields.

**Table 12: Several feeding inputs**

***Source: (Rowse, 2011).***

| Animal | Total Solids (kg/(d*a)) | Volatile Solids (kg/(d*a)) | COD (kg/(d*a)) | Nitrogen (kg/(d*a)) | Total Manure (kg/(d*a))=(L/(d*a)) | Moisture |
|---|---|---|---|---|---|---|
| Cattle - Beef finishing cattle | 2.353 | 1.895 | 1.961 | 0.163 | 29.412 92 | 92 |
| Cattle – Dairy lactating cow | 8.900 | 7.500 | 8.100 | 0.450 | 68.000 | 87 |
| Poultry- layer | 0.022 | 0.016 | 0.018 | 0.002 | 0.088 | 75 |
| Poultry- broiler | 0.027 | 0.020 | 0.022 | 0.001 | 0.102 | 74 |
| Swine- gestating sow | 1.200 | 1.000 | 1.100 | 0.085 | 12.000 | 90 |
| Swine- boar | 0.380 | 0.340 | 0.270 | 0.028 | 3.800 | 90 |
| Human faeces | * | * | * | 0.077 | 0.26 | * |

* Refers to data that could not be found

According to Rowse (2011), an OLR of 1 kg VS/($m^3$/*d) is used to quantify gas production. The OLR recommended for standard anaerobic digestion by Tchobanoglous (2003) indicate that no mixing for mesophilic involving 0.5 – 1.6 kgVS/($m^3$*d) is required. In addition, Sharma & Pellizzi (1991) suggested that a standard OLR should be 1.0 – 3.5 kgVS/($m^3$*d). Ferrer *et al*. (2009) proposed an OLR of 1.0 kgVS/($m^3$*d) or higher which is consistent with (Sharma & Pellizzi, 1991). Furthermore, Ferrer *et al*. (2009) demonstrate that 1.0kgVS/($m^3$*d) is better to 0.5 kgVS/($m^3$*d) that is recommended by Tchobanoglous (2003). Both experiments conducted by Ferrer *et al*., (2009) shows a strong correlation in biogas production. This means that there are no significant changes in the gas production yields associated with an OLR range of 0.5 – 1.0 kgVS/($m^3$*d).

The total mass of water in the manure of each species was calculated through:

$$\text{total mass}_{\text{water}} = \frac{\text{moisture*no.animals*TS}}{\text{1-moisture}} \quad \textbf{(4.3.9)}$$

Where total $\text{mass}_{\text{water}}$ = total mass of water in the total manure of one species (kg H2O/d)

moisture = mass fraction of water in the manure

TS = mass of total solids in manure generated per animal per day (kg TS/(animal*d)

no. animals = number of animals.

The TS produced daily is multiplied by the percentage of manure collected while the volume used by the liquid fraction supplemented to the reactor daily is calculated through:

Added water in the reactor,

$V_2$ ($m^3$/d)

Amount of water

supplemented to the reactor

in the liquid

fraction of

manure, $V_1$,

The volume of solids added to the reactor in the solids fraction of manure, $V_{1,s.}$ Assumed

**Figure 20: Visual Model of the Amount of Water supplemented as Water, the amount of Water supplemented as Moisture in Manure, and the number of Solids supplemented as Solids in Manure.**

***Source: (Rowse, 2011)***

The model illustrated in Figure 20 indicates the amount of water used liquefy manure solids per day. This shortens the number of days it takes to generated biogas. The volume exploited by the liquid fraction of dung supplemented to the reactor daily is immaterial hence the volume solids fraction of dung is negligible.

$$V_{1,l} = \frac{\Sigma \text{ total mass}_{water}}{P_{water}} \quad \textbf{(4.3.10)}$$

Where $V_{1,l}$ = volume of the liquid fraction of manure added per day ($m^3$)

total masswater $i$ = total mass of water in manure for species $i$ per day (kg water/d)

$i$ = animal species

$P_{water}$ = density of water ($kg/m^3$). Assumed to be 1000 $kg/m^3$ in the model, regardless of temperature.

Next, the initial concentration of volatile solids in the manure added to the reactor per day was calculated as follows:

$$C_1 = \frac{\sum C_i * V_{manure_i} * no.animals}{V_{1,l}} \quad \textbf{(4.3.11)}$$

Where C1 = initial concentration of volatile solids in the total manure volume (kg $VS/m^3$)

C$i$ = concentration of VS in manure of species $i$ (kg VS/($m^3$*d*animal)) no. animals = number of animals

V1,$l$ = volume of the liquid fraction of manure added per day ($m^3$).

The liquid and solids volume of the reactor (reactor volume not including the headspace) was calculated as follows:

$$V_R = \frac{C1 * V1,l}{OLR} \quad \textbf{(4.3.12)}$$

Where VR = liquid and solids volume of the reactor ($m^3$)

C1 = initial concentration of volatile solids in the total manure volume (kg $VS/m^3$)

V1,$l$ = volume of the liquid fraction of manure added per day ($m^3$)

OLR = organic loading rate (kgVS/($m^3$*d). Assumed to be 1.0 kgVS/($m^3$*d).

The volume of the reactor vessel, which included the gas headspace volume above the liquid, was calculated by multiplying the liquid and solids volume of the reactor by a ratio of 1.2:

Vvessel = VR*(1.2) **(4.3.13)**

Where Vvessel = volume of a reactor vessel, including the headspace ($m^3$)

VR = liquids and solids volume of the reactor ($m^3$)

### 4.3.4 Digester Range

The user input digester design model developed by Rowse (2011) applied equation 3.3.14 and 3.3.16 to quantify reactor dimensions. According to GTZ/EnDev (2010), the polyethene tube digester diameter is fixed at 1.11 and the length of the polyethene reactor is calculated through equation 3.3.14 defined as:

$$L_{polyethylene} = \frac{V_{vessel}}{\pi * \left( \left( \frac{D_{polyethylene}}{2} \right)^2 \right)} \quad \textbf{(4.3.14)}$$

Where $L_{polyethylene}$ = length of polyethene reactor (m)

Vvessel = volume of a reactor vessel, including the headspace ($m^3$)

Dpolyethylene = diameter of polyethene tube (m)

For fixed dome digester designs, the dimension is calculated by means of the H/D ratio that Nijaguna (2002) delineated as 2.0

$$D_{fixed\ tank} = \frac{V_{vessel}*4}{\left( \pi * \frac{H}{D} \right)^{1/3}} \quad \textbf{(4.3.15)}$$

Where $D_{fixed\ tank}$= diameter of fixed dome anaerobic digester (m)

$V_{vessel}$= volume of a reactor vessel, including the headspace ($m^3$)

H/D = height-to-diameter ratio (2.0 for fixed dome reactor) (dimensionless)

The height of the fixed dome reactor was calculated as follows:

$$H_{fixed\ tank} = (H/D)^* D_{fixed\ tank} \qquad \textbf{(4.3.16)}$$

Where $H_{fixed\ tank}$ = height of the fixed dome digester (m).

For floating drum digester designs, the dimension is calculated by means of equation 4.3.15 and 3.3.16 utilizing H/D ratio that Nijaguna (2002) delineated as 3.5.

### 4.3.5 Rate Kinetics and SRT

The kinetic aspect of the discussed digester design employs a semi-empirical approach to link SRT to temperature and the solubility of the feedstock (Rowse, 2011). Input factors for the kinetic part are represented by average temperature for both cold and warm season. The model utilizes a lower temperature to calculate the digester volume, however, the model outputs both the cold and warm season loading rate.

## 4.4 Development of a sustainable operational method for a South African micro-scale biodigester.

Developing projects involved four critical stages namely; project initiation, planning, implementation and conclusion (Mihelcic *et al*., 2009). The project initiation stage entails the assessment of community resources, site selection and needs analysis. Project initiation also involves feasibility studies and project preliminary designs while the implementation phase refers to the comprehensive construction and the appointment of a construction contractor. The conclusion stage refers to project finalisation and commissioning (Mihelcic *et al*., 2009). Section 4.4.1 is the proposed biodigester community integration based on the authors experience from working with communities in rolling out micro-scale digesters in rural communities. In cases where the information is sourced elsewhere, it is cited accordingly.

### 4.4.1 Proposed biodigester integration into community structures

Biodigester project developers have the necessary knowledge on the subject of anaerobic digestion. They also draw a significant amount of knowledge from development workers in terms of where biodigester could make a meaningful contribution. It is often assumed that a biodigester will contribute towards reducing energy poverty for communities living in rural areas and those not connected to the national grid, this assumption is not always correct. Project developers often have an engineering solution in the head. Nonetheless, some engineering solutions have struggled to achieve successful integration into rural communities. Needs analysis is particularly central in making sure that projects developed are successful. The importance of involving communities during the project development process, this means that community stakeholders must have first-hand information on the project development processes unfolding (Rowse, 2011).

According to Mihelcic et *al*. (2009), community development should include a social environment where the infrastructure would be installed, the beneficiaries, workers that will be responsible for operating and managing the project. In some of the digester installation that I have seen, a donor funding is sourced for the infrastructure and a desktop needs analysis is conducted and once a potential beneficiary shows interest in a biodigester, it is installed. This does not actually take into account the operational aspect of the digester except the training indicated in 4.1.3. This approach has been the major cause of digester failure. Mihelcic *et al*. (2009) indicate that needs estimation for developing a project should apply the four key steps illustrated in Figure 21. Applying the four steps approach illustrated in Figure 21 for biodigester rollout in rural in areas indicates a number of gaps in the current process that needs to be resolved. From the analysis of factors affecting the lifespan of the biodigester, it clear that[1]: 1) There are biodigester needs in rural areas; 2) The is a lack of operational technical skills from biodigester beneficiaries; 3) Problem-solving techniques are non-existence and lastly, 4) There is a lack of a strategic approach to deal with these barriers.

[1] Four step approach to project development

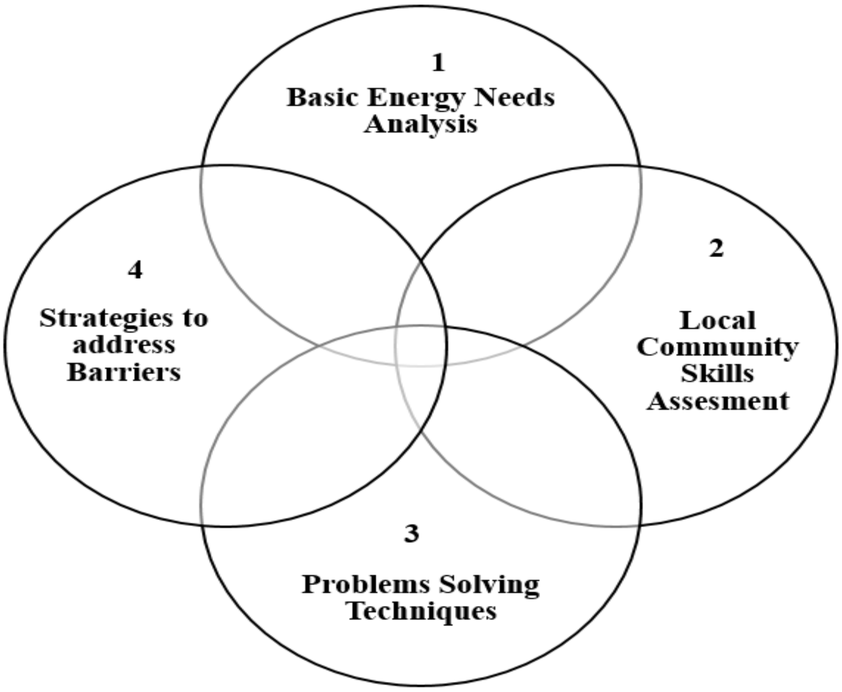



**Figure 21: A Proposed Project Development Process.**

The project integration procedure demonstrated in Figure 21 calls for the development of a sustainable operational method for micro-scale biodigester in South Africa. The policy gaps in this regards are discussed in section 4.6. Mihelcic *et al*. (2009) established a process that can strengthen project development which entails, unrestricted public outlook charting, door to door questionnaires, community structures participation, active stakeholder dialogues linking community leaders opinions, trends from partakers or non-participants as well as undertaking reviews of projects that were previously successfully executed. According to Mihelcic *et al*. (2009), community groups are usually a useful source for gaining qualitative information. This should include various community groups such as single women, children headed households, men, elderly persons, community leaders and community members with diverse economic status. Establishing community groups collects qualitative data that could not be sourced from community public meetings. Gathering data through community groups for project development highlights whether there is an interest or not from the rural communities. Through this procedure, an appropriate project management plan is developed and executed. Community cultural dynamics should be taken into account as well. This means that issues such as cooking through firewood and the negative impacts thereof could be discussed and understood by rural and uninformed communities.

Mihelcic *et al*. (2009) further explain the importance of cleanliness for the person operating digesters. However, I am of the view that for the purposes of the proposed sustainable operational method for micro-scale biodigesters, it is not ideal for rural dwellers to operate a biodigester, this should have an independent contract. Assigning a biodigester operational responsibility to community members often leads to high rates of faecal-oral disease transmitted to rural operators. Educational programmes must be developed for feedstock handlers in order to highlight the importance of hygiene and washing hands after touching feedstock. It is vitally essential to ensure that the biodigester technician resides in close proximity to where the project is being implemented. If the digester operator is reachable when the end-users are confronted with biodigester challenges, this will avoid disappointments. On the contrary, this is not feasible in South Africa, in all the digesters I have worked on, there is not a single contractor or an installer that resides in a rural area. Therefore, the proposed procedure by (Mihelcic *et al*., 2009) is considered inappropriate for South Africa.

### 4.4.2 Proposed project development approach for micro-scale biodigesters

It is important to ensure that before a micro-scale digester is installed, the correct project development approach is executed. A sustainable project development process is proposed and illustrated in Figure 21. The proposed project development approach for micro-scale biogas digesters should follow the steps indicated below:

- **Needs analysis**

Assessing digester requirements is an approach that should be applied to determine whether it would be feasible to install a micro-scale digester. This assessment should also measure energy access needs and feedstock availability. Accordingly, the estimated results should then inform whether a micro-scale biogas digesters can be installed.

- **Project preliminary designs**

Once a positive record of needs analysis is completed, preliminary designs for a viable digester needs to be finalised. The selected digester design should be based on the digester efficiency and durability features. After preliminary designs are concluded the consultation process should commence.

- **Stakeholder consultation**

At this stage, potential beneficiaries should be presented with the digester designs and impartial reasons for choosing a particular design. Project preliminary designs of feasible biogas digesters that are to be installed need to be discussed and compared with designs that have not been chosen. This should be coordinated by project funders and communal leaders who are responsible for public development. Comments, questions and concerns raised during the stakeholder consultation process should be dealt with efficiently. Decisions taken during this process should be recorded and made available to the entire stakeholder participants. This will warrant the acceptance of biodigester designs installation, whether they are communal or household micro-scale biodigesters.

- **Project final designs**

Stakeholder comments detailed during the consultation process needs to be incorporated into the digester project final designs. This can then be signed off by the established project steering committee (PSC) which should involve community representatives.

- **Construction**

After final project designs are signed off, construction of the biogas digester should commence. This process should take into account the socio-economic issues of beneficiary communities through supporting the developmental impacts during the construction phase (i.e. creating jobs locally and a new set of skills).

- **Project commissioning**

After construction is concluded, all systems and projects components should be fitted, joined together and tested. This is essential for micro-scale digesters since gas generation happens over a number of days and it is dependent on what is being fed. Project developers should confirm gas generation after project commissioning.

### 4.4.3 The proposed sustainable operational method for micro-scale biodigesters in South Africa

Sustainability is an imperative idea for the successful installation of any micro-scale biodigester. Micro-scale biogas digesters need to be sustainable since the potential of biogas utilisation is measured against the codes of sustainability. Globally, the concept of sustainability has developed in setting waste management as well as the actual durability of used technologies (Joordan, 2018). In order to guarantee sustainable operations for micro-scale in South Africa, the following operation methodology illustrated in Figure 22 is proposed (4.4.3– 4.4.5). This operational method is designed to correct the causes of digester failure identified in South Africa through this study. This is a proactive approach that draws lessons from how the general conventional power maintenance process is operated in South African.

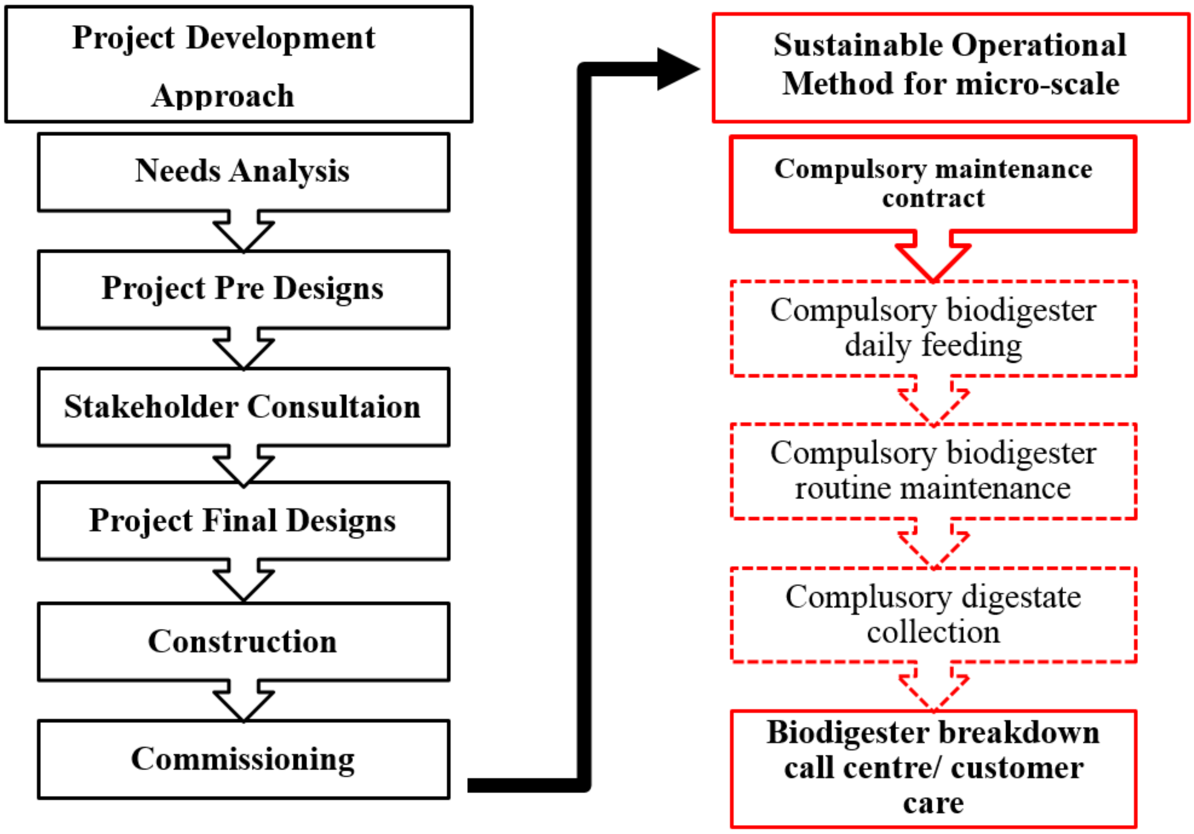



**Figure 22: A Proposed sustainable operational method for micro-scale biodigesters in South Africa.**

### 4.4.4 Proposed compulsory maintenance contract

In order to ascertain the sustainable operations of micro-scale biodigesters in South African, there is no digester that should be installed without a maintenance contract. Digesters installed in South Africa have experienced various challenges due to a lack of maintenance contract. A compulsory digester maintenance contract should be designed to deal with digestion process disturbance. The basis of the digestion process disturbance is formulated when a micro-scale digester is not operating optimally. This might be caused by the deficiency of substrate decomposition. Deficiency in the digester degradation process has a harmful effect on the economic efficiency of a biodigester plant. These deficiencies in digester operation cannot be predicted. In South Africa, biodigesters are generally used by rural dwellers that do not have access to the national grid electricity. These users are not equipped for operating nor maintaining a digester. They also do not have the necessary knowledge that can be applied for diagnosing possible digester disturbances. Therefore, it is concluded that without a compulsory maintenance contract, it not possible for South African rural dweller to be able to understand the causes of disturbance in the digestion process.  This means that if a biodigester failure occurs in the absence of an existing maintenance contract, the digester is highly likely to stop operating, regardless of the extent of the disturbance.

#### 4.4.4.1 Proposed compulsory biodigester daily feeding

According to FNR (2012), biogas generation is dependent on daily constant feeding as indicated throughout this study. Biodigester feeding has a direct impact on the quantity of microorganism produced in the digestion process. Micro-scale biodigesters utilise a through-flow feeding technique, which means that the digester operates throughout the day (FNR, 2012). The same quantity of substrate is fed into the digester daily. This feeding approach sustains a constant uniform level in the digester, which is only emptied during the digester repairs. Micro-scale biodigester users are not capacitated for operating biodigesters at this level. The lack of training indicated in section 4.1.3 would indefinitely lead to digester failures. Accordingly, in terms of the proposed sustainable operational method for micro-scale biodigesters indicated in Figure 22. A mandatory digester feeding should form part of the compulsory maintenance contract. This would guarantee a constant feeding and also assist in detecting faults in the digestion process. For an example, since feeding is required on daily basis, this means that micro-scale biodigester users will always need to ensure that there is someone available to feed in the absence of a contract for feeding. Managing this through a contract would allow rotations in terms of the digester feeding team thus freeing users from the burden of always being home for feeding purposes.

#### 4.4.4.2 Proposed compulsory biodigester routine maintenance

GIZ (2016) recognises lack of biodigester maintenance as one of the causes of digester failure. Developing biodigester maintenance contracts as part of the project design will resolve this challenge. In order to ensure a long digester lifespan, a compulsory maintenance plan is proposed to form part of micro-scale digesters that would be installed moving forward. The compulsory maintenance plan should stipulate how maintenance should be carried out. This should include maintenance intervals over the digester lifecycle. Applying a compulsory maintenance routine will warranty a sustainable operational method for micro-scale biogas digesters. Implementing the proposed compulsory routine maintenance will certainly improve the success rate of micro-scale biodigesters.

#### 4.4.4.3 Proposed compulsory digestate collection

The digestate that becomes a nutrient after the digestion process has completed should be utilised as a fertiliser (Rowse, 2011). The collection of digestate should form part of the compulsory maintenance contract. This will ensure that biodigester beneficiaries are not left with the responsibility of removing digestate. Making digestate collection a responsibility of maintenance contractors will assist in reducing the actual maintenance contract cost since the digestate has monetary value. Biodigester operators should collect and resell the digestate as a green fertiliser.  In the context of sustainable consumption and production, some farmers are willing to pay a green premium for sustainable products such as the digestate. This approach will contribute towards achieving an upward trend in a digester success rate.

### 4.4.5 Recommended biodigester (Optimisation) breakdown call centre/ customer care

Section 4.1 identified various reasons for digester breakdown. Analysing different reasons for digester failure can mainly be attributed to the lack of technical skills and a basic understanding of the anaerobic digestion process. In order to address this problem, a digester customer care in a form a call centre should be established. Biodigester beneficiaries should know whom to contact if their digester malfunctions. This approach will optimise digester fault detection and parameter monitoring. Maintenance contractors will begin to identify similar trends that result in digester failure and recommend corrective action instruments in order to optimise the proposed sustainable operational method for biodigesters.

## 4.5 Analysis of an economic and market model for a micro-scale biodigester

Micro-scale biodigester model structure in South Africa involves donor-funded digesters. These projects are on many occasions implemented through government-funded entities with an objective to encourage end-users to accept the technology (Msibi, 2015). Msibi (2015) maintains that this approach has not produced an extensive adoption of the technology and an active market development. The African national biogas programme which was implemented in nine African countries has resulted in a 44% increase in biodigester installations between 2011 and 2012 (Msibi, 2015). However, a number of biodigesters that are currently operational cannot be verified since 60% of the digesters that were installed in 2007 failed (Msibi, 2015).

According to Rajendran *et al*. (2012), biogas generated through micro-scale digesters is utilised for cooking. Biogas volume is in the range of 30 and 45 $m^3$ monthly, this number can easily be compared to traditional energy sources such as firewood, cow dung and kerosene. Liquefied Petroleum Gas (LPG) is in the range of 11 and 15 kilograms (KG) while kerosene is between 15 and 20 litres monthly (Rajendran *et al*., 2012). Most biodigesters have a lifecycle of between 25 and 30 years (Mukherjee, 1974). Based on the price that was charged for the Three Crowns High School biodigester, it is concluded that digesters should cost between R13 700 and R17 000 as indicated in Table 13. Regrettably, micro-scale digesters cost approximately R40 000.00 in South Africa (Ruffini, 2013). The payback period (PBP) of a biodigester is dependent on digester type (Ferrer *et al*., 2009). Inflated micro-scale digester prices make it financially unavailable, especially if it is compared with electricity connection fees prescribed by under the INEP (i.e. costing around R20 000.00 per connection). Some consultants inflate a 6m$^3$ micro-scale household biodigester up to R52 000.00 (see Figure 33: Biogas Pro 6 (6 m$^3$) quotation in July 2018). Biogas stove is sold for R 1 750.00 (See Appendix: D), this makes micro-scale biodigesters unaffordable.

**Table 13: Micro-scale digester installation estimation cost**

| **Description** | **Unit** | **Quantity** | **Rate** | **Cost in Rand** | **Workforce cost** | **Cumulative at 6% inflation Amount in 2017** |
|---|---|---|---|---|---|---|
| GroundWork | m$^3$ | 3.43 | R100 | R343 | | R486 |
| Mould cost | sum | 1 | R1 000 | R1000 | | R1 418 |
| Rotamoulded segments (4mx3mx7m) | sum | 3 | R3 080 | R9 240 | | R13 107 |
| Welding of segments | sum | 3 | 100 | R300 | R180 | R680 |
| Paddlewheel platforms and pipping | sum | 2 | 300 | R600 | R400 | R1 418 |
| **Total cost** | | | | | | **R 17 109** |

KVIC is an old model that has been broadly recognised and adopted for numerous household biodigester designs (Rajendran *et al*., 2012). This design comprises a mobile inverted drum located on a well-shaped biodigester. It has a steel drum responsible for gas storage situated on the bottom of the biodigester. This steel drum is capable of shifting up and down depending on the quantity of stored gas at the upper section of the biodigester. The heaviness of the inverted steel drum spread over the pressure required for the gas to flow through the pipeline for utilisation (Rajendran *et al*., 2012).

Rajendran *et al*. (2012), quantifies biodigester PBP using the deenbandhu, KVIC, and janta models. The deenbandhu model indicated the lowest PBP approximately 4.7 and 1.6 years for a household micro-scale digester size of 1 – 6 $m^3$. The second short PBP is the janta model with roughly 11.3 PBP and 3.2 years for biodigester sizes of 1 – 6 $m^3$. Rajendran *et al*. (2012), shows a high payback period of 26.6 years for 1 $m^3$ floating drum digester. Amigun & von Blottnitz (2009) applies the Lang factor (fL) to quantify capital cost for diverse biodigesters sizes. The fL provides better estimates for micro-scale, medium and large scale digesters PBP (Amigun & von Blottnitz, 2009). Rubab & Kandpal (1995) applies a different model for quantifying biodigester capital cost, which includes parameters such as the size of a digester plant, digester components, economies of scale, HRT and other investment cost data. Rajendran *et al*. (2012), explain that varied models are used to calculate digester cost and benefits associated with using a micro-scale biogas digester. A financial model to assess the cost-effectiveness of a micro-scale biodigester was developed by (Georgakak *et al*., 2003; Rajendran *et al*., 2012). The Basic Economic Evaluation Model (BEEM) were altered to be more effective, this is known as the Modified Basic Economic Evaluation Model (MBEEM). This improvement entails a number of parameters like, computerised optimum HRT which is 20 days, net present benefit grows with government aid, high firewood price and a decline in digester cost (Rajendran *et al*., 2012). The net present benefit gets affected by high interest rates, while financially viability of a digester stabilises with an increased digester size. According to Ciotola *et al.* (2011), using firewood for cooking defeats the biogas feasibility in circumstance were digester efficiency over 25%. Digester efficiency that is over 25%puts the biogas plant at a much-compromised situation. This will worsen if the feedstock cost is sold while firewood is available for free. Energy and environmental impact assessment conducted by Ciotola *et al*. (2011) found that micro-scale biogas should be used for cooking rather than generating electricity. Environmental Sustainability Index (ESI) used to estimate the total sustainability of a digester and the Environmental Loading Ratio (ELR) is used to measure serious environmental impacts. Higher ELR indicates excessive environmental stress.

Equation 4.3.17 represents a net present benefit, whereas PW denotes the present worth of the increasing net benefit. Where *Ag* – represents yearly increment benefit from using micro-scale biogas as cooking fuel. *Af* – represents yearly increment benefit from using treated slurry as fertilizer and *C* – denotes Cost of a digester, *N* – indicates Plant lifecycle, and *W* – shows inflation rate/interest rate (Bala & Hossain, 1992).

$$PW = (A_g + A_f)\sum_{n=1}^{N} W^n - C - \sum_{n=1}^{N} m_n \qquad \textbf{(4.3.17)}$$

Equation 4.3.18. Models the cost-benefit analysis for a floating drum micro-scale biogas, where NPV – represents Net Present Value. $A_b$ shows annual benefits, $A_C$ shows the annual operating cost, *i* represents interest rate, *t* represents the lifecycle of the biogas plant, *C* denotes Cost of the digester (Kandpal *et al*., 1991).

$$NPV = \frac{(A_b - A_c)[1-(1+i)^{-t}]}{i} - C \qquad \textbf{(4.3.18)}$$

Equation 4.319. Broad cost estimation for a biogas digester, where *C* represents a cost of a biodigester, $C_O$ represents a cost of the reference plant, a and b are coefficients, *V* represents a volume of a digester, $V_O$ represents the volume of the reference digester (Kandpal *et al*., 1991).

$$c = C_0[a + b\left(\frac{V}{V_0}\right)] \qquad \textbf{(4.3.19)}$$

Equation 4.3.20. Modified basic economic evaluation model, where – *NPV* represents Net Present Value (Rand), *NCF* – represents Net Cash Flow, *r* – represents discount rate, *j* – represents operational lifecycle of a digester (year), *I* – represents a capital investment, adapted from (Georgakak *et al*, 2003).

$$NPV = \sum_{j=1}^{n}[NCF_j \times (1 + r)^{-j}] - I \qquad \textbf{(4.3.20)}$$

Pütz *et al*. (2011) established a morphological matrix to create a profit margin from biogas produced, this was achieved by selling to low-income farmers. Correct biogas transportation methods when selling biogas can yield proceeds to both the seller and the buyer. This means that biogas producers can generate, store and distribute gas when it is required. According to Li *et al*. (2007), building biogas digesters using quantitative processes allows ecological and environmental benefits to be quantified. The calculation for economic and environmental proceeds is indicated in equation 4.3.21 and 4.3.22. Peter *et al*. (2009) established an experimental model for the acceptance of biogas technology, and the outcomes displayed that the adoption of micro-scale digester increases with high earnings which have a direct correlation with cattle owned, bigger homes and hike in fuel price. Nonetheless, the adoption of biogas technology declined with a growth in the remote location and household setups. About 58.5% of those that have micro-scale biodigesters can take three meals a day and improve their health conditions (Van Groenendaal & Gehua, 2010). Feng *et al*. (2009) quantified the efficiency of energy provision by means of a biogas digester for rural households. Evaluation of the current setting and the innovative change that take place over time indicated the prominence of the biogas not only in economic terms but also through contributions to a sustainable healthier lifestyle.

Equation 4.3.21. Measures economic benefits of a digester, where $T_c$ represents a cost of economic benefits for a household, *m* refers to items consuming energy, *n* represents available energy resources, *j* represents type of usage, *I* represents type of resource, $C_i$ denotes unit price for the type of energy to Li *et al*. (2007).

$$T_c = \sum_{j=1}^{m} \sum_{i=1}^{n} C_i x_{ij} \; (i = 1,2 \ldots n, j = 1,2 \ldots m) \qquad \textbf{(4.3.21)}$$

Equation 4.3.22. Calculations for green benefits of a digester, where $T_s$ represents cost of environmental benefits for a household, *m* refers to items consuming energy, *n* represents kinds of energy resources, *j* denotes type of usage, *I* refers to type of resource, $S_{1i}$ represents Environmental costs in a hill, $S_{2i}$ represents environmental costs in a slope Li *et al*. (2007).

$$T_s = \sum_{j=1}^{m} \sum_{i=1}^{n} x_{ij} \, (S_{1i} + S_{2i})(i = 1,2 \ldots n, j = 1,2 \ldots m) \qquad \textbf{(4.3.22)}$$

#### 4.5.1 Micro-scale biodigester proposed as a technique for poverty reduction

Poverty has been rising in South Africa. This is evidenced in the latest poverty statistics that indicate that although there is a broad decline in poverty between 2006 and 2011, South African poverty levels increased in 2015 (Stats SA, 2017). Figure 23 indicates that over 50% of the South African populations were confirmed poor in 2015, the poverty headcount grew to 55.5% from 53.2% in 2011. The upper-bound poverty line (UBPL) in South Africa is R992 per person per monthly, this is measured approximately 30.4 million South Africans living in poverty in 2015 (Stats SA, 2017).

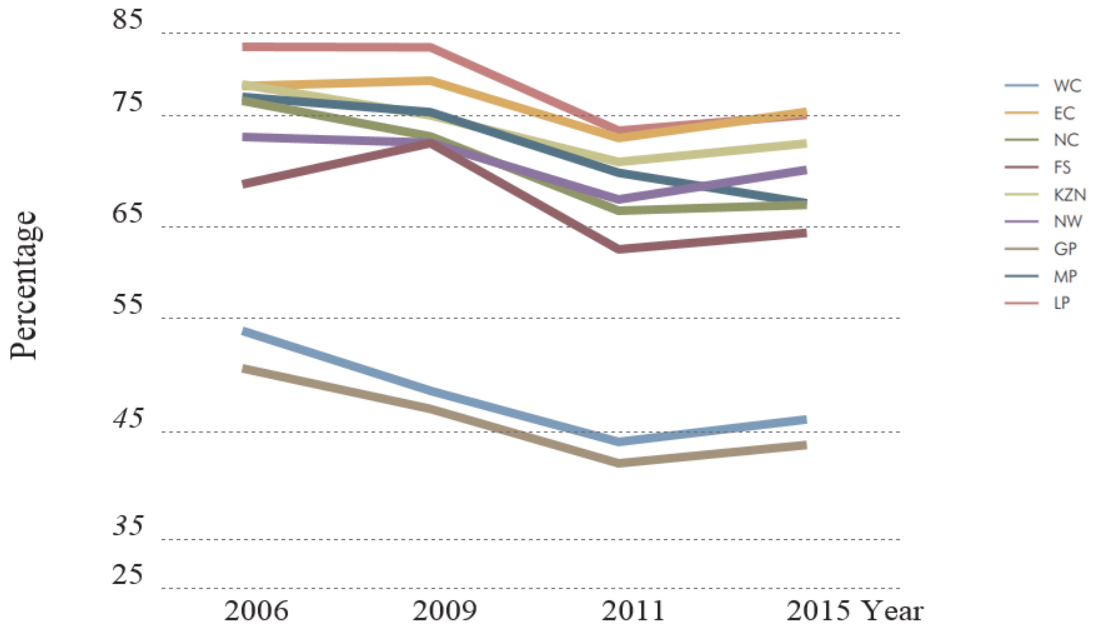



**Figure 23: South African poverty headcount by age**
***Source: (StatsSA, 2017).***

Females, living in rural areas, such as the Eastern Cape and Limpopo, and those with little or no education are confronted by poverty. This includes children aged 17 years and younger as illustrated in Figure 23. A trend worth noting is that state of poverty appear to decline as one gets older and start over again from age of 55 onwards (StatsSA, 2017). Biodigesters contribute to economic development through job creation and poverty reduction. In Nepal, around 11000 people are working in the biogas industry (Msibi, 2015). Msibi (2015) indicates that this development has activated a yearly demand for kerosene to decline by 7.7 million litres. This equates to a saving of about $2.1 million per annum (Msibi, 2015). Socio-economic benefits associated with biogas digester utilisation reduces workload for women and children since there are responsible for collecting firewood.

### 4.5.2 A Proposed funding model for micro-scale biodigester

The average employment and compensation ratio illustrated in Appendix: I and the poverty share per province indicated in Figure 24 and (Appendix: I) demonstrates that residents in rural municipalities earn lesser income compared to urban dwellers, due to socio-economic conditions and low skills levels existing in rural communities. Appendix: I indicates an employment and compensation by skill earnings of R 1.2 million in Eastern Cape while employment by skill in Gauteng province has R5.3 million in earnings. The earnings discrepancies between urban and rural illustrated in Figure 24 and (Appendix: I) indicates that urban provinces have higher employment, compensation and skills rates, thus higher affordability rate. Nonetheless, biodigesters are needed in rural areas where there is currently lower skills and employment rates, subsequently, lower affordability ratios, see poverty share by province in Figure 24.

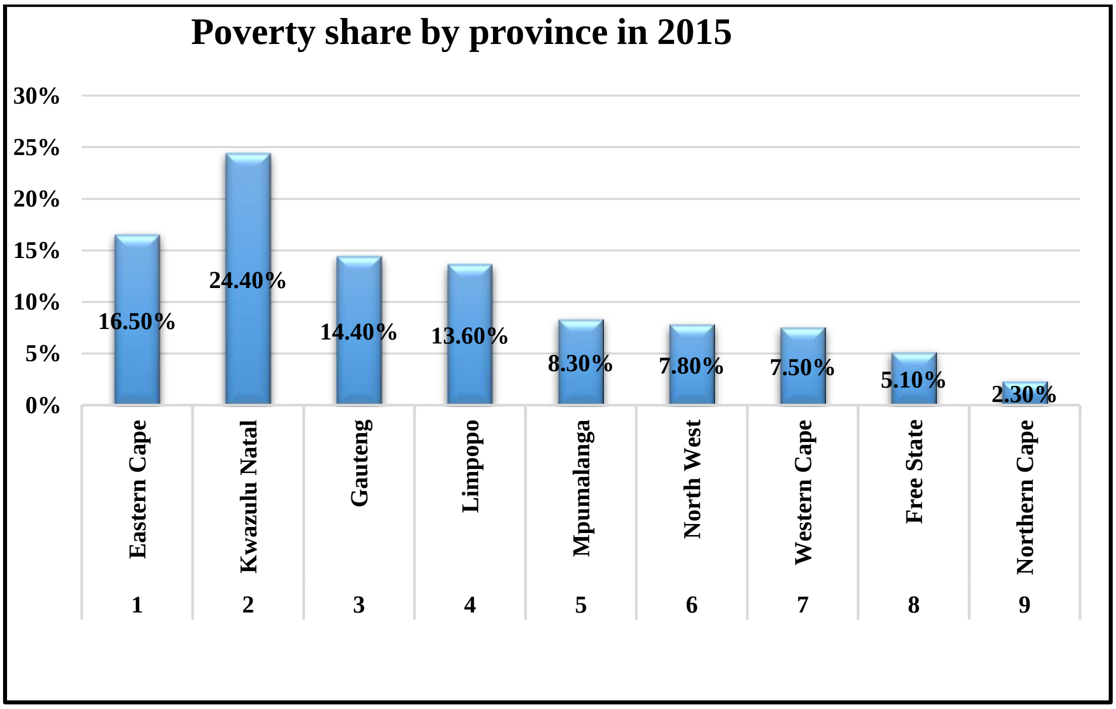



**Figure 24: Poverty share by province in 2015**

***Source: (StatsSA, 2017)***

The income and expenditure for rural provinces is minimal. Figure 25 indicates a low income and expenditure patterns in provinces like Eastern Cape, Mpumalanga and Limpopo and Northern Cape. Residents in these areas are unable to afford to pay for biodigester. In order for micro-scale digesters to be adopted in rural communities, the government needs to regulate the digester cost and provide subsidies for rural dwellers. This will assist in curbing biodigester overpricing and make it economical while exorbitant pricing is managed through the provision of subsidies. Moreover, the provision of biodigester subsidies for rural inhabitants and those that are not connected to the national grid represents an opportunity for adopting digesters in South Africa. The poor who are likely to continue burning firewood in the absence of micro-scale biodigesters will be more exposed to health risks. The negative impacts of cutting and burning wood will indirectly cost the government through the public health system.

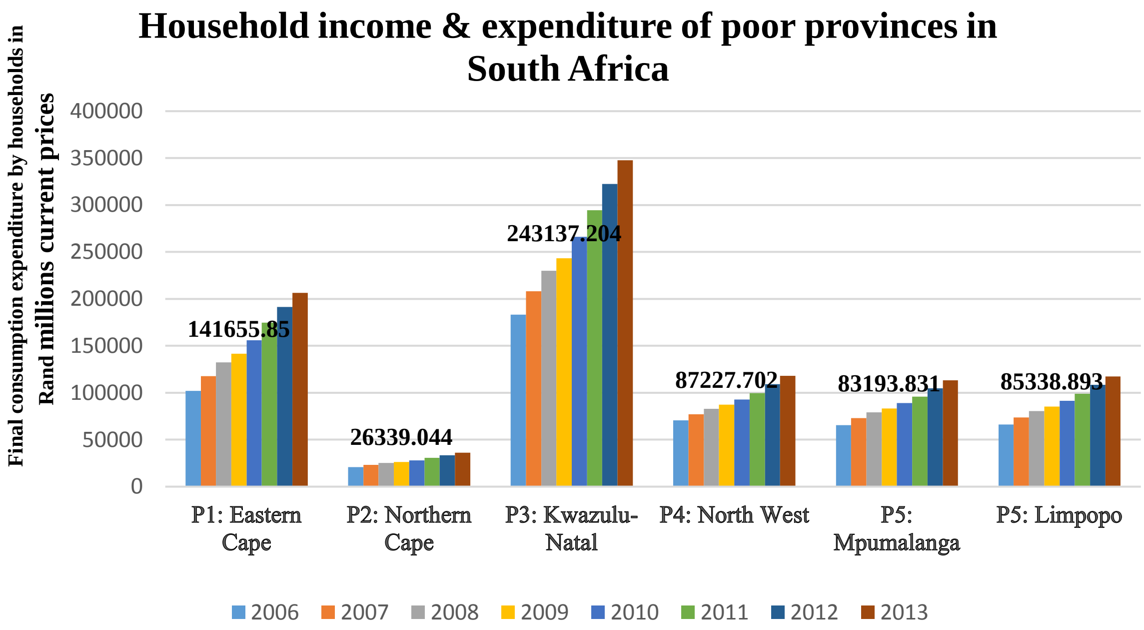



**Figure 25: Poor provinces income & expenditure**

***Source: (Quantec, 2018b).***

### 4.6 Review of policy for micro-scale biodigester

Clean energy policy analysis in South Africa indicate that the current strategic framework is not fully structured to stimulate the distribution of micro-scale digesters (Valenti, 2015). The main objective of the South African energy policy framework indicated in the White Paper on Energy Policy (DME, 1998) are as follows:

- Increasing access to cheap energy;

Micro-scale biodigesters play a role in providing basic energy needs for those that are not connected to the national grid. While the White Paper highlights this as an objective, we still have a significant number of rural households that do not have electricity. Section 4.1 indicated challenges that micro-scale biogas digesters have encountered while trying to improve energy access. Electrification has been a traditional way of providing electricity in South Africa, this has indirectly contributed to the underdevelopment of other technologies that are capable of stimulating energy access (Winkler, 2006). Winkler (2006) point out that in 1993 only about 36% of the South African population had access to electricity. Significant progress has been made to date, however, the focused has been on concentrated areas like townships and urban areas. Scatters households found in rural areas have not benefitted in the electrification successes.

- Improving energy governance;

According to Winkler (2006), the energy policy objective meant to improve governance refers to introducing competitiveness in the electricity generation. The evolution of electricity generation before 1994 was dominated by the consolidation of state-owned entities. Early private power producers were gradually taken over by Eskom which became responsible for new energy supply. The main drivers for the increased concentration and public ownership of the industry were potential economies of scale in power plants which required large amounts of capital that could be facilitated by government guarantees. Electricity is seen as an essential element for the government industrialisation strategy because then the state assumed that playing a dominant role in key infrastructure industries, such as rail, air, and sea transport, telecommunications, water, coal-based synthetic fuels, nuclear energy, iron and steel industries was critical for stimulating the South African economic growth. Competition and private ownership in these sectors were perceived to be non-optimal since the state viewed these industries as key instruments for industrialisation, employment creation and economic development (Eberhard, 2007).

- Promoting economic development;

In achieving the 1998 energy policy White Paper objectives of economic development, cheap electricity cost and resource efficiency were meant to play a part in stimulating economic growth. Optimum application of energy efficiency promotes high levels of economic production with less amount of energy usage. This reduces the input cost of production while the outputs increases. In the context of micro-scale biogas digesters, economic development could be promoted through small business development that could be established due to the availability of energy in unelectrified rural areas (Winkler, 2006).

- Securing supply through an energy mix;

The 1998 energy policy White Paper aims to create an energy mix by means of introducing cleaner energy production sources (DME, 1998). Micro-scale biogas digesters provide energy through displacing methane gas that could have been atmospheric. Varied sources of energy supply improve flexibility, principally, in situations where energy users cannot be supplied by one source of energy (Winkler, 2006). In 2003, South Africa approved an additional policy paper on renewable energy (DME, 2003). The 2003 energy white paper indicate the South African government goal to stimulate the introduction of cleaner sources of energy.

- Controlling energy and environmental impacts.

Environmental effects related to energy sources used by those that have no grid electricity triggers high amounts of GHG emissions. Biogas production is regarded as environmentally responsive since the $CO_2$ connected to biogas combustion is reabsorbed during the growth of fodder and foodstuffs processing (Msibi, 2015).

### 4.6.1 Lack of biogas policy in South Africa

The current existing South African energy policy does not cover micro-scale biogas digesters unambiguously. In 2013, the biogas production industry gains some momentum, however, the lack of a policy framework was absent to sustain the development (Joordan, 2018). In 2016, motivation in the biogas development was once more encouraged through the development of a national biogas strategy that was being developed by the DoE, however, the national biogas strategy was retracted. This conduct does not yield policy certainty for micro-scale biogas digesters. The South African Gas Act 48 of 2001 stipulates the following:

- The production or importation of gas;
- An activity referred to in Schedule 1 and 2 of the Gas Act.

**Schedule 1 and 2 of the Gas Act provides lists with the following activities**:

- Transmission of gas for own use
- Small biogas projects in rural communities
- Gas reticulation and any trading incidental thereto
- LPG supplied from a bulk storage tank or cylinder

Besides the registration requirements indicated in the Gas Act, 48 of 2001 there are no other additional requirements.

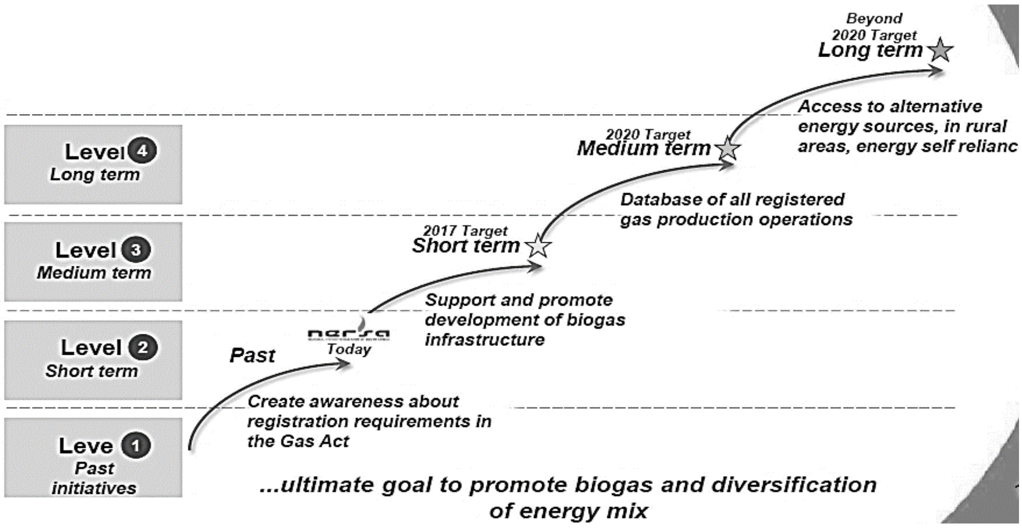



**Figure 26: Gas regulation**

**Source: (Nersa, *2017).***

Figure 26 highlights focus areas of the Gas Act 48 of 2001, which is mainly, creating awareness, supporting the development of biogas infrastructure, registration of all gas production facilities and alternative access to energy in rural areas. The current policy does not mention any funding plan although it focusing in rural areas. The safety standards and installation guidelines regulation are also non-existent. These challenges need to be resolved. Although energy access is a recognised challenge in rural areas, the lack of energy in rural results in minimal economic activities. Figure 27 indicates that gas only contributes about 2.5% of the South African energy mix. Imported natural gas (NG) is utilised for industrial sectors purposes, power generation, vehicular fuel and residential areas (Nersa, 2017). The current legislation poses the following challenges for micro-scale biogas:

- No definition of micro-scale biogas projects;
- Gas reticulation currently regulated by Municipalities – not within NERSA's jurisdiction;
- Act only mentions the transmission of gas for own use – distribution excluded.

**Industry challenges**

- Lack of sufficient awareness of registration requirements in the Gas Act;
- Many facilities already in operations prior to registration;
- Compliance requirements for individual households;
- Funding for biogas production facilities in rural households.

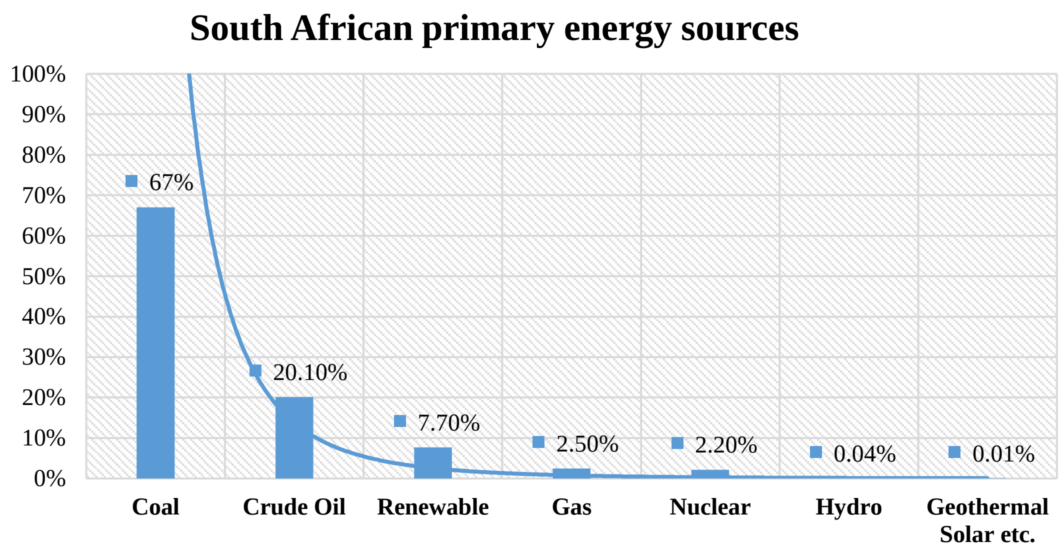



**Figure 27: South African primary Energy Sources**

***Source: (DoE, 2016)***

### 4.6.2 Proposed micro-scale biogas policy

Micro-scale biodigester adoption requires a clear policy in order to ensure that all stakeholders are cognisant of their roles and responsibilities in the household biogas value chain. The proposed micro-scale biogas digester policy should cover the following segments:

- Classification of micro-scale biodigester sizing (i.e. define the minimum and maximum for micro-scale digester);
- Classification of all feedstock that should be utilised for all micro-scale biodigesters;
- Price guidelines which regulate the cost micro-scale biodigester installers should charge (i.e. tax exemption, subsidies and support aid to enable biogas utilisation);
- Biodigester quality (i.e. safety standards, lifespan warranties and guarantees);
- Certification/ accreditation of micro-scale biodigester installers;
- Compulsory biodigester maintenance through a certified/ accredited maintenance officer;
- Biogas slurry management and sorting (i.e. biogas fertilizer management utilization and pricing regulation);
- Awareness campaigns for rural communities;
- Set a registration deadline for operational micro-scale biodigester;
- Penalties for non-compliance

# CHAPTER 5

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The aim of this research was to investigate a sustainable operational method for a biodigester in South Africa. The research further evaluated the biogas production process in order to understand reasons for the short lifespan of digesters and causes for digester failure in South Africa. Mainly, it was found that the leading cause for digester failure was due to lack of technical skills and assigning the responsibility operating and maintaining digester to end-users. This was found to have accelerated the short lifespan for biodigesters. The local market model of micro-scale bio-digester was evaluated and policy gaps such as micro-scale overpricing, lack of certified biodigester installers and lack of maintenance were identified as the main reasons for digester failure among others. Policy gaps make digesters adoption sluggish. The few micro-scale biodigesters that have been installed in South Africa have set a complex trend for the biogas technology adoption. Lack of energy provision in rural areas continues to exclude the poor from participating meaningfully in the South African economy. It was found that the socio-economic benefits of micro-scale biogas digesters can create jobs in rural areas. In addition, adopting micro-scale biodigesters will reduce climate change impacts and promote economic development in rural communities.

The economic and market model analysis showed that prices that are currently charged for micro-scale biodigesters are expensive. The target market cannot afford micro-scale digester without government funding. Levels of poverty in rural communities are high, this renders micro-scale digesters financially unviable at the current charge rates.

## 5.2 Recommendation

It is recommended that the proposed sustainable operational method for micro-scale biodigester should be accepted and adopted as a long-term solution to deal with biodigester failure. Secondly, the identified gaps in the Gas Act of 48 of 2001 that indicate a lack of safety standards, micro-scale digester sizing, feedstock guidelines, digester cost regulation, installer certification, compulsory maintenance, awareness campaigns for rural communities and registration deadline for operating micro-scale biodigester should be resolved through amending the Gas Act of 2001. An introduction of penalties for non-compliance with the recommended Gas Act amendments is recommended. Thirdly, incentives and a clean energy fund for rural communities is recommended under the INEP program of the Department of Energy (DoE). This is meant to promote equal access to basic energy services for all South Africans. This approach is in line with the introduction of the clean energy mix and the need to reduce carbon emissions in South Africa. Lastly, an electronic feeding and utilisation of the internet for monitoring digester performance is recommended. This should be investigated as a tool that could enhance biodigester efficiency.

Incentive programmes such as the Department of Trade and Industry's Manufacturing Competitiveness Enhancement Programme and Eskom rebate for small-scale renewables needs to include micro-scale biodigesters. The motivation for such incentives is mainly driven by the universal energy access programme, climate change, job creation and rural economy advancement. Generally, there is limited awareness of micro-scale biogas in South Africa. To date, South Africa does not have a biogas strategy or a policy that regulates the micro-scale biogas sector. For the proposed sustainable micro-scale biodigester method to be implemented correctly, the following needs to done before a miro-scale digester is implemented.

- The digester needs analysis must be conducted;
- Preliminary designs that could be presented to digester end-users should be done before the stakeholder consolation process takes place;
- Inputs and comments gathered from the consultation process needs to incorporate to final digester designs;
- Biodigester maintenance contract should be in place for all digesters that will be installed.

Executing the proposed sustainable operational method and reviewing policy gaps will result in a sustainable adoption of micro-scale biodigesters, energy poverty reduction and economic growth stimulation for rural communities and those that are still not connected to the national grid. Constant routine feeding will enhance the lifespan of a digester and promote the adoption of biogas technology at the household level.

## REFERENCE

Aklaku, E. D., Jones, K. & Obiri-Danso, K. (2006). Integrated biological treatment and biogas production in a small-scale slaughterhouse in rural Ghana. *Water Environment Research, 78*(12), 2335-2336-2339.

Al Imam, F.I., Khan, M. Z. H., Sarkar, M. A. R. & Ali, S. M. (2013). Development of biogas processing from cow dung, poultry waste, and water hyacinth.*International Journal of Natural and Applied Science*, 2(1), 13-17.

Al Seadi, T., Rutz D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. & Janssen, R. (2008). *Biogas handbook.* Southern Denmark Esbjerg: University of Southern Denmark. ISBN:978-87-992962.

Amigun, B. & von Blottnitz, H. (2009). Capital cost prediction for biogas installations in Africa: Lang factor approach. *Environmental Progress and Sustainable Energy*, 28(1), 134–142.

Bagher, A.M., Fatemeh, G., Saman, M. & Leili, M.M. (2015). Advantages and Disadvantages of Biogas Energy. *Bulletin of Advanced Scientific Research*, 1 (5), 132-135.

Bala, B.K. & Hossain, M.M. (1992). Economics of biogas digesters in Bangladesh. *Energy*. 17(10), 939 – 944.

Banout, J. et al. (2016) 'Addressing problems at small-scale biogas plants : a case study from central Vietnam', 112, pp. 2784–2792. doi: 10.1016/j.jclepro.2015.09.114.

Brent, A. (2014). The agricultural sector as a biofuels producer in South Africa. *Understanding the Food Energy Water Nexus*. WWF-SA, South Africa. Available from: http://www.fewlbnexus.uct.ac.za/sites/default/files/image_tool/images/91/6__a16270_the_agricultural_sector_as_a_biofuels_producer_in_sa___online.pdf. (Accessed 26 March 2017).

Cambell, K. (2017). South African Bio-energy Atlas launched to support bio-energy development. *Engineering News*. 24 March 2017.

Cheng, S., Li, Z., Mang, H., Huba, E., Gao, R. & Wang, X. (2014). Development and application of prefabricated biogas digesters in developing countries. *Renewable and Sustainable Energy Reviews* 34, 387 – 400.

Ciotola, R.J., Lansing, S. & Martin, J.F. (2011). Emergy analysis of biogas production and electricity generation from small-scale agricultural digesters. *Ecological Engineering*. 37(11), 1681–1691.

Colombo, E., Bologna, S. & Masera, D. (Eds.). (2013). Modern Energies Services for Cooking. *Renewable Energy for Unleashing Sustainable Development*. DOI 10.1007/978-3-319-00284-2.

Cote, C., Masse, D., Quessy, S. (2006). Reduction of indicator and pathogenic microorganisms by psychrophilic anaerobic digestion in swine slurries. *Bioresource Technology*, 97, 686-691.

Davidson, O., Winkler, H., Kenny, A., Prasad, G., Nkomo, J., Sparks, D., Howells, M., Alfstad, T., Mwakasonda, S., Cowan, B. & Visagie, E. (2006). Energy policies for sustainable development in South Africa, Options for the future. Energy Research Centre, University of Cape Town. Available from: https://open.uct.ac.za/bitstream/handle/11427/16747/Winkler_Energy_policies_for_2006.pdf?sequence=1. (Accessed 29 July 2017).

DfID (Department for International Development). (2011). Potential of Small-Scale Biogas digesters in Sub-Saharan Africa. Interdisciplinary Expert Workshop. 16-18 May 2011. Addis Ababa, Ethiopia. Available from: http://r4d.dfid.gov.uk/PDF/Outputs/Energy/60820_workshop-Addis-Ababa-16-18May-2011.pdf (Accessed 26 March 2017).

DME (Department of Minerals and Energy). (1998). White Paper on Energy Policy for South Africa. Pretoria, DME.

DME (Department of Minerals and Energy). (2003). White Paper on renewable energy. South Africa. Pretoria, DME.

DoE (Department of Energy). (2015). *State of Renewable Energy in South Africa*. Available from: http://www.gov.za/sites/www.gov.za/files/State%20of%20Renewable%20Energy%20in%20South%20Africa_s.pdf (Accessed15 March 2017).

DoE (Department of Energy). (2016). Vote 26 Annual Report 2015/16. Department of Energy. Pretoria, Republic of South Africa. ISBN: 978-0-621-44952-5.

Feng, T., Cheng, S., Min, Q. & Li, W. (2009). Productive use of bioenergy for rural household in ecological fragile area, panam county, tibet in China: The case of the residential biogas model. *Renew. Sustain. Energy Rev.* 13(8), 2070–2078.

Ferrer, I., Gamiz, M., Almeida, M. & Ruiz, A. (2009). Pilot project of biogas production from pig manure and urine mixture at ambient temperature in Ventanilla (Lima, Peru).*Waste Management, 29*(1) 168-173.

FNR (Fachagentur Nachwachsende Rohstoffe e. V.). (2012). *Guide to Biogas From production to use*. Available from: https://mediathek.fnr.de/media/downloadable/files/samples/g/u/guide_biogas_engl_2012.pdf

FoN (Finishes of Nature). (2011). Integrated biogas pilot for rural schools. Installation of pilot system at three crowns school final report. Available from: http://www.finishesofnature.co.za/Three-Crowns-School/ (Accesses 15 February 2017).

Gagnon, K., Peoples, S. & Bloniasz, C. (2014). *Turning Waste into Heat: Designing an Anaerobic Digester to Extend the Growing Season for Small Scale Urban Farmers*. Unpublished degree thesis. Worcester: Worcester Polytechnic Institute. Available from: https://web.wpi.edu/Pubs/E-project/Available/E-project-101614-164946/unrestricted/DigesterA13_Final_Draft.pdf. (Accessed 7 September 2017).

Garfi, M., Ferrer-Marti, L., Villegas, V. & Ferrer, I. (2011). Psychrophilic anaerobic digestion of guinea pig manure in low-cost tubular digesters at high altitude.

Georgakakis, D., Christopoulou, N., Chatziathanassiou, A. & Venetis, T. (2003). Development and use of an economic evaluation model to assess establishment of local centralized rural biogas plants in Greece. *Applied Biochemistry and Biotechnology*. 109(1-3), 275–284.

Ghimire, P.C (2013). SNV supported domestic biogas programmes in Asia and Africa. *Renewable Energy, 49,* 90-94.

GIZ & SABIA. (2016). Biogas Industry in South Africa. Assessment of the skills needs and estimation of the job potential for the biogas industry in South Africa. *Published by the South African-German Energy Programme (SAGEN)*, Pretoria, South Africa. Available from: http://www.sagen.org.za/publications/19-assessment-of-skills-needs-and-estimation-of-the-job-potential-for-the-biogas-industry-in-south-africa (Accessed 21 March 2018).

GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH). (2015). Biogas Development in South Africa. Analysis of Licensing and Permitting Processes. Available from: http://www.biogasassociation.co.za/wp.../04/GIZ-SAGEN-Biogas-Licensing-Analysis.pdf (Accessed 16 October 2017).

GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH). (2016). *Analysis of the existing small-scale biogas projects in the Eastern Cape*. South Africa.

Gosling, D. (1982).Biogas for Thailand's rural development. Transferring the technology. *Biomass*, 2, 309–316.

GTZ/EnDev (2010). *Installation manual for low-cost polyethylene tube digesters*. Germany.

(German Technical Cooperation Agency)

Hach (2011). EPA Compliant Methods. Available from: http://www.hach.com/epa (Accessed, 30 October, 2017).

Haig, K. & Gorgens, J. (2013). Process Technologies for BioEnergy. In: Hugo W. (Ed). (2015). South African BioEnergy Atlas. Pretoria: Department of Science and Technology, Section W07_01. Available from: http://app01.saeon.ac.za/PLATFORM_4/BEA/WIKI/WP07/WP07_01_BEA_PROCESSES.PDF. (Accessed 7 July 2017).

Hugo, W (Ed), (2016). BioEnergy Atlas for South Africa – Synopsis Report, Department of Science and Technology, Pretoria, South Africa Available from: http://www.dst.gov.za/images/2017/2017_pdfs/Bio-Energy-Atlas_DevV15.pdf. (Accessed 30 March 2017).

IBBK (International Biogas and Bioenergy Centre of Competence) (2014). 1st Agro-industrial Biogas Training Seminar and Study Tour, University of Cape Town, Western Cape, South Africa.

IRENA (International Renewable Energy Agency). (2016). *Measuring small-scale biogas capacity and production, International Renewable Energy Agency*, Abu Dhabi.

Joordan, G.P. (2018). Evaluating the sustainable potential of biogas generation in South Africa. Published MSc (Sustainable Agriculture) thesis. Stellenbosch: Stellenbosch University.

Kandpal, T.C., Joshi, B. & Sinha, C.S. (1991). Economics of family sized biogas plants in India. *Energy Conversion Management*. 32 (2), 101–113.

Karekezi, S. & Kihyoma, W. Renewableenergy in Africa: Prospects and limits. In *Proceedings of the Workshop for African energy experts on oper-ationalizing the NEPAD energy initiative*, Dakar, 2–4 June 2013.

Khanal, S. (2009). *Anaerobic biotechnology for bioenergy production*. Published online: March 27, 2009. DOI: 10.1002/9780813804545.

Kim, M., Ahn, Y.H. & Speece, R. E. (2002). Comparative process stability and efficiency of anaerobic digestion; mesophilic vs. thermophilic. *Water Research*, 36(17), 4369-4385. doi: http://dx.doi.org/10.1016/S0043-1354(02)00147-1

Kitchen, R. and Tate, N.J. (2000). *Conducting Research in Human Geography: Theory, Methodology and Practice*, Prentice Hall, Harlow, England.

Kolver, L. (2013). Nersa registers six KZN biogas production operations. *Engineering News*. Available from: http://www.engineeringnews.co.za/article/nersa-registers-six-kzn-biogas-production-operations-2013-10-28 (Accessed 14 June 2018).

Lahav, O., & Morgan, B. E. (2004). Titration methodologies for monitoring of anaerobic in developing countries – a review. *Journal of Chemical Technology and Biotechnology*, 79, 1331-1341.

Lang, N. L., & Smith, S. R. (2008). Time and temperature inactivation kinetics of enteric bacteria relevant to sewage sludge treatment processes for agricultural use. *Water Research, 42*(8-9), 2229-2241. doi: 10.1016/j.watres.2007.12.001.

Lee, Y., Chung, Y. C., Jung, J. Y. (2008). Effects of chemical and enzymatic treatments on the hydrolysis of swine waste water. *Water and Science Technology*, 58(7), 1529- 1534.

Li, G.Z., Niu, S.W. & Liang, Y.H. Estimate on the Ecological and Economic Benefits of Rural Household Biogas Construction Project in Loess Hilly Region, China. In *Proceedings of International Conference on Wireless Communications: Networking and Mobile Computing*, 21–25 September 2007.

Lloyd, P. (2014). Challenges in household energisation and the poor**.** *Journal of Energy in Southern Africa*, 25 (2), 2-8.

Luo, T., Zhu, N., Shen, F., Long, E., Long, Y., Chen, X. & Mei, Z. (2016). A Case Study Assessment of the Suitability of Small-Scale Biogas Plants to the Dispersed Agricultural Structure of China. DOI 10.1007/s12649-016-9487-3.

Manyi-Loh, C.E., Mamphweli, S., Meyer, E.L., Okoh, A.I., Makaka, G. & Simon, M. (2013). Microbial Anaerobic Digestion (Bio-Digesters) as an Approach to the Decontamination of Animal Wastes in Pollution Control and the Generation of Renewable Energy. *International Journal of Environmental Research and Public Health*, 10(9) 4390-4417 Doi:10.3390/ijerph10094390.

McCarty, P. L. (1964). Anaerobic waste treatment fundamentals. *Public Works*, *95*(9-12), 107-112.

Mensah, K.A & Forster, C.F. (2003). An examination of the effects of detergents on anaerobic digestion. *Bioresource Technology*, 90(2), 101-228.

Metcalf & Eddy. (1979). Wastewater Engineering: Collection, Treatment, Disposal, McGraw-Hill, New York.

Mihelcic, J. R., Fry, L. M., Myre, E. A., Phillips, L. D., & Barkdoll, B. D. (2009). *Field guide to environmental engineering for development workers: Water, sanitation, and indoor air*. Reston, VA: American Society of Civil Engineers.

Msibi, S.S. (2015). Potential for domestic biogas as household energy supply in South Africa. Published MSc (Applied Science) thesis. University of Pretoria.

Mukherjee, K.K. (1974). *Gobar Gas Plant – A Study*. *Gandhi Peace Foundation*. New Delhi, India.

Mukumba, P., Makaka, G. & Mamphweli, S. (2016a). Biogas Technology in South Africa, Problems, Challenges and Solutions. *International Journal of Sustainable Energy and Environmental Research*, 5 (4) 58-69. doi:10.18488/journal.13/2016.5.4/13.4.58.69.

Mukumba, P., Makaka, G. & Mamphweli, S. (2016b). Anaerobic digestion of donkey dung for biogas production. *South African Journal of Science*, 112 (7/8) 1-4.

Mulinda, C., Hu, Q. & Pan, K. (2013). Dissemination and Problems of African Biogas Technology. *Energy and Power Engineering*, 5, 506-512. http://dx.doi.org/10.4236/epe.2013.58055

Nersa (National Energy Regulator of South Africa). Regulation of Biogas - Nersa. In *Proceedings of the 3rd National Biogas Conference,* Midrand, South Africa, 1 – 3 November 2017.

Nijaguna, B. T. (2002). *Biogas technology* (1st ed.). Delhi, India: New Age International Ltd.

Pandor, N. 2017, April 06. Guiding nation's optimum adoption of bioenergy. *Mail & Guardian*.

Banout, J. *et al.* (2016) 'Addressing problems at small-scale biogas plants : a case study from central Vietnam', 112, pp. 2784–2792. doi: 10.1016/j.jclepro.2015.09.114.

Muvhiiwa, R. *et al.* (2017) 'The impact and challenges of sustainable biogas implementation : moving towards a bio-based economy'. Energy, Sustainability and Society, 7(20). doi: 10.1186/s13705-017-0122-3.

Parawira, W. (2009) 'Biogas technology in sub-Saharan Africa : status , prospects and constraints', (8), pp. 187–200. doi: 10.1007/s11157-009-9148-0.

Tucho, G. T. *et al.* (2016) 'Problems with Biogas Implementation in Developing Countries from the Perspective of', (July 2018). doi: 10.3390/en9090750.

Peter, N.W., Mugisha, J. & Drake, L. (2009). Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. *Energy Policy*, 37(7), 2754–2762.

Pütz, K., Asfaw, A., Leta, B. & Müller, J. Biogas as Business-Biogas Transport Technology and Economic Concept for Developing Countries. In *Proceedings of Conference on International Research on Food Security, Natural Resource Management and Rural Development*, Bonn, Germany, 5 – 7 October 2011.

Quantec (Quantec EasyData). (2018a). Data Set: REMP—Labour - Employment and compensation by skill level, industry and 2011 local municipal/ward-based metro region level. Pretoria, South Africa.

Quantec (Quantec EasyData). (2018b). Data Set: RIES—Household income & expenditure by 2006 local municipality 1995-2013. Pretoria, South Africa.

Rajendran, K., Aslanzadeh S. & Taherzadeh, M.J (2012). Household Biogas Digesters – A Review. *Energies*, 5, 2911-2942; doi:10.3390/en5082911.

Rao, P., Barai, S.S., Dey, R. & Mutnuri, S. (2010). Biogas generation potential by anaerobic digestion for sustainable energy development in India. *Renewable and Sustainable Energy Review*, 14(7): 2086-2094.

Rittmann, B. E. & McCarty, P. L. (2001). *Environmental biotechnology: Principles and applications* (International ed.). Singapore: McGraw Hill.

Roopnarain, A. & Adeleke, R. (2017). Current status, hurdles and future prospects of biogas digestion technology in Africa. *Renewable and Sustainable Energy Reviews*. 67(2017), 1162–1179.

Rowse, L.E. (2011). *Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries*. Published MSc thesis. Tampa: University of South Florida. Available from: http://network.bepress.com/hgg/discipline/439?utm_source=scholarcommons.usf.edu%2Fetd%2F3324&utm_medium=PDF&utm_campaign=PDFCoverPages. (Accessed 28 September 2017).

Rubab, S. & Kandpal, T.C. (1995). Cost of anaerobic digestion technology: Household biogas plants in India. *International Journal on Energy Research*, 19(8), 675–685.

Ruffini, A. (2013). SA not using its biogas potential. *ESI Africa: Africa's Power Journal*. Available from: https://www.esi-africa.com/sa-not-using-its-biogas-potential/. (Accessed 14 April 2018).

SABIA (South African Biogas Industry Association). Conversations around challenges and opportunities. *A report on the first National Biogas Conference*. Midrand, South Africa, 30–31October 2013. Available from: http://www.energy.gov.za/files/biogas/2013-National-Biogas-Conference-Report.pdf

Sharma, N. & Pellizzi, G. (1991). Anaerobic biotechnology and developing-countries: 1. technical status. *Energy Conversion and Management*, *32*(5), 447-469. doi:10.1016/0196-8904(91)90006 5.

Singh, K (2010). *Study of solar/biogas hybrid power generation*. Published MEng dissertation. Patiala: Thapar University. Available from:

http://dspace.thapar.edu:8080/dspace/bitstream/10266/1244/3/1244.pdf. (Accessed 21 March 2017).

Speece, R. E. (1996). *Anaerobic biotechnology for industrial wastewaters* (1st ed.). Nashville, TN, USA: Archae Press.

Stafford, W. (2013). Waste Water: Organic Component and Utilisation. Work Package WP04_02, South African BioEnergy Atlas. Pretoria: Department of Science and Technology. Available from: http://app01.saeon.ac.za/PLATFORM_4/BEA/WIKI/WP04/WP04_02_WIKI_WasteWater.PDF. (Accessed 7 July 2017).

StatsSA (Statistic South Africa). (2009). Changed in standard of living among population groups in South Africa 1998-2006. Available from: http://www.statssa.gov.za/publications/Report-03-03-02/Report-03-03-02.pdf (Accessed 11 February 2018).

StatsSA (Statistic South Africa). (2011). Agricultural household. Pretoria, South Africa.

StatsSA (Statistic South Africa). (2014). General Household Survey. Available from: http://www.statssa.gov.za/publications/P0318/P03182014.pdf (Accessed 11 February 2018).

StatsSA (Statistic South Africa). (2017). Poverty Trends in South Africa. An examination of absolute poverty between 2006 and 2015. Available from: https://www.statssa.gov.za/publications/Report-03-10-06/Report-03-10-062015.pdf (Accessed 15 July 2018).

Tchobanoglous. G., Burton, F.L., & Stensel, H. D. (Eds.). (2003). *Wastewater Engineering: Treatment and reuse*. McGraw Hill, New York.

Tiepelt, M. (2015). Status quo of the biogas sector development in South Africa as well as the way forward. *GIZ SAGEN Short-term Biogas Training Seminar*. Pretoria, South Africa, 10 June 2015.

Thom, C (1994). The application of biogas technology in South Africa for small-scale energy production. Published. MSc thesis. Cape Town: University of Cape Town.

Tucho, G. T. et al. (2016) 'Problems with Biogas Implementation in Developing Countries from the Perspective of', (July 2018). doi: 10.3390/en9090750.

Valenti, D. (2015). Diversifying South Africa's renewable energy mix through policy. Published MSc thesis. Stellenbosch: Stellenbosch University.

Van Groenendaal, & W. Gehua, W. (2010). Microanalysis of the benefits of China's family-size bio-digesters. *Energy*, 35(11), 4457–4466.

Van Hessen; J. (2014). *An Assessment of Small-Scale Biodigester Programmes in the Developing World: The SNV and Hivos Approach*. Environment and Resource Management Research Project. Amsterdam: University Amsterdam.

Vesilind, P. A. (Eds.). (1998). *Wastewater treatment plant design* (4th ed.). London, UK and Alexandria, VA, USA: IWA Publishing and the Water Environment Federation.

Vijay, V.K., R. Kapoor., A. Trivedi & V. Vijay. 2015: Biogas as Clean Fuel for Cooking and Transportation Needs in India. Ravindra, P. (Ed.). *Advances in Bioprocess Technology*. DOI 10.1007/978-3-319-17915-5.

Vögeli Y., Lohri, C. R., Gallardo, A., Diener, S. & Zurbrügg, C. (2014). *Anaerobic digestion of biowaste in developing countries: Practical information and casestudies*, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf. Available from: http://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/SWM/Anaerobic_Digestion/biowaste.pdf. (Accessed 7 July 2017).

Winkler, H. (2006). *Energy policies for sustainable development in South Africa's residential and electricity sectors*. Published (Energy Research Centre) PhD Thesis. Cape Town: University of Cape Town.

## APPENDIX

## APPENDIX: A

# Guiding nation's optimum adoption of bioenergy

FOREWORD
**Naledi Pandor**

The global need to move to cleaner and more sustainable energy systems means that we should continuously evaluate various energy feedstock and generation pathways for heat, power and transport fuels. These include bioenergy-based options (bioenergy is renewable energy made available from biological materials such as wood or manure).

According to the REN21 (Renewable Energy Policy Network for the 21st Century) Global Status Report, bioenergy accounts for roughly 10% of the world's primary energy supply, and has remained at about this level since 2005. In developing countries, most bioenergy is consumed inefficiently when used for cooking and heating, and poses health hazards that include smoke inhalation. However, in most developed economies, bioenergy has been incorporated into modern energy services and is a significant contributor to the energy industry, and thus to the bio-economy.

As South Africa formalises the establishment of the bioenergy industry, the principles of inclusivity, addressing energy poverty and stimulating economic opportunities are among the key driving factors, as government continues exploring ways of providing energy to communities currently not receiving such services. This is in line with the department of science and technology's commitment of living up to its mandate, to use science and technology to improve the country's economy, create employment and improve the quality of life of all citizens. The department's 2015-2020 Strategic Plan is part of the vision of the National Development Plan to tackle the interlinked challenges of poverty, inequality and unemployment.

The web-based Bioenergy Atlas will assist government by making available information on potential energy resources, their geographic spread, their proximity to infrastructure, and potential end-users. This decision-support tool is expected to guide energy planning and investments, as well as the deployment of bioenergy-based technologies, including the co-firing of biomass, the use of residues to produce biofuels, and bio-digesters for domestic energy needs.

The many requests for Bioenergy Atlas data by various players (policy-makers, power utilities, industry and academia) in the national system of innovation during the development of the atlas have been encouraging, and government looks forward to its wider application.

The Bioenergy Atlas preliminary assessments (based on potential contributions by subsistence farmers, municipal organic waste, waste-water treatment works, agriculture, forestry residues, etcetera) indicate significant potential in the Eastern Cape, Mpumalanga, KwaZulu-Natal, the Western Cape, Gauteng and Limpopo.

Development of a bioenergy industry could have a significant impact on job creation (seasonal and permanent) and improve energy access.

The bioenergy sector will be supported within a policy framework that ensures that bioenergy-based socioeconomic development does not compromise food security, biodiversity or water security, and that will guide future energy infrastructure installations for both central and distributed generation.

My department is very pleased to contribute to South Africa's transition to renewable energy, and will continue to support research to improve the competitiveness of local innovations in this sector.

**Naledi Pandor is the Minister of Science and Technology**

# New bioenergy atlas heralds South Africa's energy generation future

South Africa's first bioenergy atlas has been hailed as a positive step towards transforming the country into a low carbon and future clean energy hub in Africa, while simultaneously creating jobs.

The department of science and technology has launched the Bioenergy Atlas of South Africa to provide information on potential bioenergy resources and their geographic spread, proximity to infrastructure and socioeconomic impact, as well as relevant conversion technologies and feasible end-use applications.

Unlike energy sources that are generated through fossil fuels like coal, oil and gas, renewable energy is a clean energy source that can contribute approximately 3 500MW of electricity equivalent to the national energy mix over the planning horizon of 20 years.

Together with the Wind Energy Atlas of the department of energy, the Carbon Sinks Atlas of the department of environmental affairs and the Renewable Energy Toolkit as developed by Promethium Carbon to guide project development on mine-impacted land, the energy atlas is set to play an important role in establishing this low carbon future.

Most importantly, the development of a bioenergy industry could have a significant impact on job creation, seasonal and permanent, while improving access to energy.

As a resource fully exploited, the potential impact with respect to energy access is estimated at 864 000 people and job creation potential of at least 125 000, including seasonal jobs.

## Biomass job creation

### Number who may benefit from job creation in the biomass cultivation or harvesting sectors

| PROVINCE | DISTRICT | NUMBER OF LOW-INCOME HOUSEHOLDS IN CATCHMENT AREA | NUMBER OF BIOMASS HARVESTING JOBS | NUMBER OF BIOMASS PROCESSING JOBS | ADDITIONAL GROSS VALUE ADDED | % OF CURRENT GROSS VALUE ADDED |
|---|---|---|---|---|---|---|
| Mpumalanga | Gert Sibande | 211 710 | 17 417 | 916 | R3 275-million | 6% |
| Gauteng | Ekurhuleni | 1 509 496 | 6 666 | 487 | R1 740-million | 0% |
| Eastern Cape | Chris Hani | 152 021 | 61 536 | 480 | R1 714-million | 11% |
| KwaZulu-Natal | Umgungundlovu | 613 521 | 14 968 | 479 | R1 712-million | 1% |
| Eastern Cape | Alfred Nzo | 226 961 | 55 328 | 408 | R1 456-million | 8% |
| Western Cape | Overberg | 386 253 | 3 219 | 272 | R971-million | 1% |
| Western Cape | Eden | 56 303 | 935 | 228 | R814-million | 9% |
| Eastern Cape | Cacadu | 267 735 | 9 870 | 226 | R807-million | 2% |
| Free State | Thabo Mofutsanyane | 75 287 | 2 548 | 204 | R728-million | 9% |
| KwaZulu-Natal | Zululand | 117 665 | 25 601 | 180 | R643-million | 6% |
| TOTALS | | 3 616 952 | 198 088 | 3 880 | R13 861-million | 2% |

Graphic: JOHN McCANN Data source: SA BIOENERGY ATLAS

The atlas projections of a percentage of the low-income population that can benefit from access to energy is 17% in the Eastern Cape (125 000 people), 34% in Kwa-Zulu Natal (365 000 people), 34% in Limpopo (268 000 people), and 22% in North West (106 000 people).

In addition, populations may benefit from seasonal job creation in the biomass cultivation or harvesting sectors; as many as 60 000 jobs in the Eastern Cape, 35 000 in KwaZulu-Natal, and 30 000 in Limpopo.

The estimates of manufacturing and processing jobs in the major rural areas are approximately 2 000 jobs in the Eastern Cape, 700 jobs in KwaZulu-Natal and 300 jobs in Limpopo.

**To page 3**

**Figure 28: Guiding the nation’s optimum adoption of bioenergy**

***Source: (Pandor, 2017)***

**Appendix: B**

**Figure 29: (Left) Ferro Digester Design (Right) Bamboo Digester Design**

***Source: (Cheng et al., 2014).***


**Figure 30: (Left) Biodigester installation in Vietnam**

**(Right) Appropriate Rural Technology Institute**

***Source: (Cheng et al. 2014).***

## Appendix: C

**Figure 31: Micro-scale digester cycle – biogas stove from a $12m^3$ fixed dome biogas digester installed in Melani (Eastern Cape) Village early childhood development centre.**

**Appendix: D**

FINISHES OF Nature

**Quote:**

To: East London Childcare and youth centre
No 5 Summit road.
Beacon Bay
East London
5205

From: Finishes of Nature
156 Magenta Place
Morganbay, 5292

Quote No 054/16/10/2014

Reg No: CK 2001/044775/23

VAT Reg: 4800199657

**RE: Integrated Biogas, Rainwater Harvesting & Food Gardens to support the Agro-ecological Development at the day care centre Beaconbay.**

| Description | Amount |
|---|---|
| To the installation of one Biogas Pro 6 agricultural digester, to feed the garden with nutrient rich fertilizer. And biogas to the kitchen.<br><br>Biogas stove puxin auto ignition<br>Gas volume / flow meter installed | R 52 740.00<br><br>R 1 750.00<br>R 3460.00 |
| To install 1 x 5000 liter rain tank, including base and gutters complete: | R14 400.00 |
| To Establishment of raised bed agroecological gardens linked to the biogas digester with three days intensive training and knowledge transfer.<br><br>Compost and biomass/mulch<br><br>**Sub total Material construction** | R 11 400.00<br><br>R 3800.00<br><br>R 87 550.00 |
| Three site monitoring visits over three months | R 13 440.00 |
| Site vist and assessment<br>Final site visit and commitioning of system | R 4 080.00<br>R 4 080.00 |
| SUB-TOTAL | R 109 150.00 |
| VAT @ 14% | R 15 281.00 |
| **TOTAL incl Vat** | **R 134 411.70** |

**Figure 32: Biogas Pro 6 (6 m$^3$) quotation in October 2014**

## Appendix: E

**FINISHES OF NATURE GLOBAL (PTY) LTD.**

30a Da Gama Industrial Park
Arnoldton, East London, 5201
Tel.: +27 72 127 4477
Fax: +27 86 600 1461
e-mail: thulani.bono@gmail.com

**QUOTATION**

| | | | |
|---|---|---|---|
| Attention: | Stanley Semelane | Date: | 26 Jul 2018 |
| Position: | Energy Industry Research Group | Reg. No.: | 2012/148728/07 |
| Co/Dept: | CSIR: Energy Centre | VAT No.: | 4010266593 |
| Section: | CSIR, Meiring Naude Road, Pretoria | Bid Ref.: | **BP6M** |
| Tel/Cell: | +27 12 841 3464/+27 65 856 3373 | Quote No.: | **CSIR 1819-1** |
| Fax: | | | |
| E-mail: | ssemelane@csir.co.za | Prepared By: | **Thulani Bono** |

| Item No.: | Quantity | Description | Unit Price | | Total | |
|---|---|---|---|---|---|---|
| | | **6m3 Agama Biogas Digester Installation** | | | **R** | **90,100.00** |
| 1 | 1 | Agama Biogas Pro 6m3 Digester Installed | R | 32,500.00 | R | 32,500.00 |
| 2 | 1 | Agama Biogas Pro Delivery | R | 5,200.00 | R | 5,200.00 |
| | | **Description of Works** | | | | |
| 3 | 1 | Pipe connections | R | 2,500.00 | R | 2,500.00 |
| 4 | 1 | Boiling table commercial 2 burner | R | 4,800.00 | R | 4,800.00 |
| 5 | 1 | Gas Feeds (20m est.) | R | 4,600.00 | R | 4,600.00 |
| 6 | 1 | Macerator with stainless steel sink | R | 18,000.00 | R | 18,000.00 |
| 7 | 1 | Polishing Dam | R | 2,500.00 | R | 2,500.00 |
| 8 | 1 | Civil works or box | R | 20,000.00 | R | 20,000.00 |

| | | |
|---|---|---|
| **SUB TOTAL** | **R** | **90,100.00** |
| **VAT** | **R** | **13,515.00** |
| **TOTAL PRICE** | **R** | **103,615.00** |

**Figure 33: Biogas Pro 6 (6 m$^3$) quotation in July 2018**

**Appendix: F**

## FINISHES OF NATURE GLOBAL (PTY) LTD.

30a Da Gama Industrial Park
Arnoldton, East London, 5201
Tel.: +27 72 127 4477
Fax: +27 86 600 1461
e-mail: thulani.bono@gmail.com

## QUOTATION

| | | | |
|---|---|---|---|
| Attention: | Stanley Semelane | Date: | 26 Jul 2018 |
| Position: | Energy Industry Research Group | Reg. No.: | 2012/148728/07 |
| Co/Dept: | CSIR: Energy Centre | VAT No.: | 4010266593 |
| Section: | CSIR, Meiring Naude Road, Pretoria | Bid Ref.: | **BP12M** |
| Tel/Cell: | +27 12 841 3464/+27 65 856 3373 | Quote No.: | **CSIR 1819-2** |
| Fax: | | | |
| E-mail: | ssemelane@csir.co.za | Prepared By: | **Thulani Bono** |

| Item No.: | Quantity | Description | | Unit Price | | Total |
|---|---|---|---|---|---|---|
| | | **12m3 Agama Biogas Digester Installation** | | | **R** | **149,100.00** |
| 1 | 1 | Agama Biogas Pro 6m3 Digester Installed | R | 65,000.00 | R | 65,000.00 |
| 2 | 1 | Agama Biogas Pro Delivery | R | 10,400.00 | R | 10,400.00 |
| | | **Description of Works** | | | | |
| 3 | 1 | Pipe connections | R | 3,800.00 | R | 3,800.00 |
| 4 | 1 | Boiling table commercial 2 burner | R | 4,800.00 | R | 4,800.00 |
| 5 | 1 | Gas Feeds (20m est.) | R | 4,600.00 | R | 4,600.00 |
| 6 | 1 | Macerator with stainless steel sink | R | 18,000.00 | R | 18,000.00 |
| 7 | 1 | Polishing Dam | R | 2,500.00 | R | 2,500.00 |
| 8 | 1 | Civil works or box | R | 40,000.00 | R | 40,000.00 |

| | | |
|---|---|---|
| **SUB TOTAL** | **R** | **149,100.00** |
| **VAT** | **R** | **22,365.00** |
| **TOTAL PRICE** | **R** | **171,465.00** |

**Figure 34: Biogas Pro 6 (12 m$^3$) quotation in July 2018**

**Appendix: G**

**Extremely High Reliability**

***Quality*** *– Manufacture takes place in a tightly controlled factory environment, using only the best quality Linear Low Density Polyethylene (LLDPE)*

***Installation*** *– Installation is performed using certified plumbers and gas practitioners in accordance with SANS 1200, 100087 & 827.*

**Mechanical specifications**

- *Reactor volume:* *4,050 litres*
- *Gas store volume:* *950 litres*
- *Expansion volume:* *1,000 litres*
- *Total volume:* *6,000 litres*
- *Access chambers:* *520 mm diameter*
- *Max gas pressure:* *6.75 kPa*
- *Dimensions - BiogasPro-6:*
  - *Diameter: 2,160 mm*
  - *Height: 2,225 mm*
  - *Weight: 230 kg*
  - *Wall thickness: 8 – 11 mm*
  - *Sewer inlet depth: 330 mm*

**Figure 35: Agama Biogas-Pro digester before installation & Specification from the quotation.**

**Appendix: H**

**Figure 36: Jobs created through construction of a biodigester.**

## Appendix: I

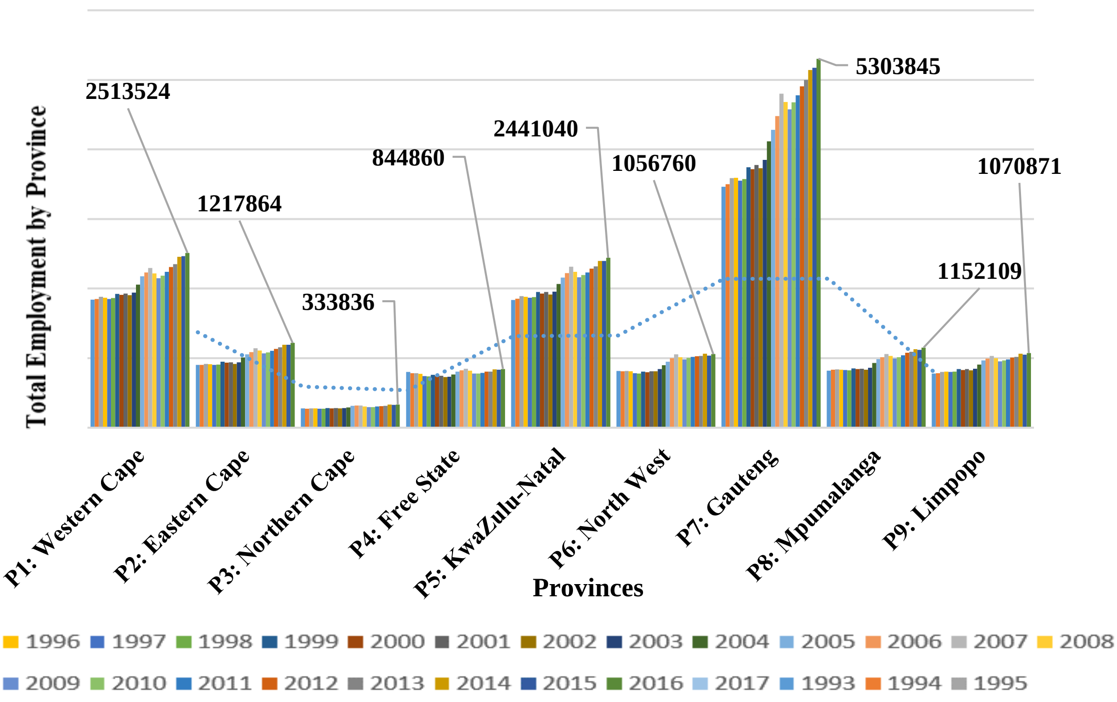



**Figure 37: Employment and compensation by skill ratio**

***Source: (Quantec, 2018a).***

## Appendix: J


| Session: G Track: Engineering and Technology | | | | | |
|---|---|---|---|---|---|
| Session Chair: Prof. James Chipeta | | Co-Session Chair: Dr Setlhaolo | Moderator: Dr. J. Shindano | Co-Moderator: Dr. Pardon Mwansa | Time Keeper: Mr. Lungu Dryson |
| Time | Paper ID | Author | Institution | Country | Paper Title |
| 08:00-08:20 | CFP/867/2018 | Dr. Tebogo Mashifana | University of Johannesburg | South Africa | Evaluation of chemically treated and lime stabilised gold mine tailings: effect on unconfined compressive strength |
| 08:20-08:40 | CFP/898/2018 | Mr. Maphumzane Stanley Semelane | CSIR | South Africa | Investigating a sustainable operation method for a micro-scale biodigester in South Africa |
| 08:40-09:00 | CFP/871/2018 | Mr. Enose Moholisa | Council for Scientific and Industrial Research(CSIR) | South Africa | Benefits of integrating various PV system configurations in the supply mix of a South African commercial entity |
| 09:00-09:20 | CFP/853/2018 | Ms. Naomi Zulu | Information and Communications University | Zambia | Impact of Boscia senegalensis on Clay Turbidity in ponds. |
| 09:20-09:40 | CFP/838/2018 | Mr. Mainza Chilanga | INFORMATION AND COMMUNICATIONS UNIVERSITY | Zambia | Design and Development of the Computer Numerically Controlled (CNC) Router |
| 09:40-10:00 | CFP/700/2018 | Mr. Andrew Ose Phiri | Afrospace Architects | Zambia | AFROBLOCK, Interlocking Block Masonry |
| 10:00-10:20 | CFP/630/2018 | Mr. Adam Chileshe | Nortec | Zambia | Review of Fracture Detection and Characterization Techniques |
| 10:20-10:40 | CFP/582/2018 | Mr. Charles Chomba Chomba | Information Communication University | Zambia | Digital Image Authentication |
| 10:40-11:00 | CFP/388/2017 | Mr. Emmanuel Zingapeta | The Copperbelt University | Zambia | Improving Aerodynamic Efficiency of NACA 4216 Airfoil Using Computational Fluid Dynamics Analysis and XFoil |
| 11:00 – 11:20 TEA/COFFEE BREAK | | | | | |

**Figure 38: Conference presentation programme**

## Appendix: K (Paper published)

# A sustainable operational method for micro-scale biodigesters in South Africa

M. Stanley Semelane*, Henerica Tazvinga*
Energy Centre, Council for Scientific and Industrial Research, Pretoria, South Africa
ssemelane@csir.co.za, htazvinga@csir.co.za

B. Diakanua Nkazi
Oil and Gas Production and Processing Research Unit, School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, South Africa
Diakanua.nkazi@wits.ac.za

***Abstract*—This paper proposes a sustainable operational method for micro-scale biodigesters in South Africa. The findings indicate a compulsory maintenance contract that ensures constant digester feeding for microorganism sustenance is essential. A routine maintenance plan to ensure that all digester mechanical failures are minimized is also recommended. It expected that the proposed sustainable operational method for this technology will contribute towards energy access to millions of people in South Africa and globally as well as achieving national sustainable development goals objectives. The methodology can also result in increased uptake of this technology even by those that are connected to the national grid as a way of reducing their energy bills. This paper also highlights the high cost of micro-scale biogas digesters is a key hindrance for small-scale biogas digester rollout.**

***Keywords*—micro-scale biodigester; biogas; sustainable operational method; energy poverty**

### I. Introduction

Energy is an essential element for stimulating economic growth, social development, human welfare and improving living standards. Over the years, dependence on fossil fuels has increased significantly, and concerns about greenhouse gas (GHG) emissions have also increased prompting an increase in adoption of renewables and other cleaner sources of energy [1]. Current world energy consumption is roughly about 15 terawatts (TW) and renewable energy only contributes about 7.8% of the total global energy supply [2]. Energy demand for Sub-Saharan Africa is approximately 4% of the global energy consumption, which does not match with the sub-Saharan Africa population estimated to be about 13% of global inhabitants [2]. Biomass can play a role in the transition to a low carbon economy. Biogas technology is a proven technology that can provide both electrical and thermal energy for use by households. This technology has been implemented in many countries and the successes and failures of biogas programs are well documented in the literature [3]. Micro-scale biodigester technology utilization has significantly increased in Asia although the uptake in Sub-Saharan Africa has, up to now, been sluggish regardless of national and international efforts aimed at supporting biogas technology adoption [4]. Uptake of this technology, as with other renewable energy technologies, depends on many factors some of which are country specific. The African national biogas programme which was implemented in nine African countries - resulted in a 44% increase in biodigester installations between 2011 and 2012 and the number of biodigesters that are operational is currently unknown since 60% of the digesters that were installed after 2007 have failed [5].

A failing biogas project, regardless of the size, has unfavourable consequences on the general perceptions and adoption of micro-scale biodigester technology. Proposing a sustainable operational method for micro-scale biodigester in South Africa comes as a direct response that seeks to understand the fundamental limitations for the successful implementation of micro-scale biodigesters in South Africa. Biogas plants provide critical advantages in the area of waste management and produce organic-rich by-products in the form of fertilizer. Various factors that hinder the uptake rate of household biodigesters are well documented in South Africa, however, the main challenge is limited feedstock and relatively low numbers of cattle in South Africa when compared to India and China who produce 28% and 19% (respectively) of cattle globally [4]. Another challenge is the unavailability of land and water. Most South African rural communities face water supply challenges. Another cause for a slow uptake is the lack of proficiency and awareness of the benefits of using biogas technology.

Economic development scenarios that are represented in this paper are attributable to identified domestic and communal micro-scale biodigester project options for households with four or more cows. Analysis of an economic and market model for a micro-scale biodigester showed that sustainable operation of a biodigester is cost-competitive to baseline energy sources such as fuelwood, cow dung, kerosene and Liquefied Petroleum Gas [6]. It is expected that the results of this work will contribute to the South African energy policy update in relation to the role of micro-scale biodigesters. Biogas programs have been rolled out by private companies, Non-Governmental Organisations and also by the Department of Energy (DoE) in some parts of South Africa, however, currently there is no clear policy framework and enabling instruments for sustainable biodigester operations. Analysis of the South African Gas Act 48 of 2001 only indicates digester registration as a legal requirement. This work will highlight the environmental and socio-economic benefits attributable to sustainable biodigester operation. This will also contribute towards the improvement of the livelihoods of rural dwellers that are still confronted with basic energy supply challenges.

----End----