Potential benefits and experienced challenges of small household biogas-digesters for rural households

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This thesis is submitted for the degree of Master of Science

March 2016

To my closest Friends and Family:

Thank you for all your support, in my difficult but beautiful education process.

Thank you for letting me dream.

Thank you for believing and trusting in me.

Writing these words makes me remember the long road that led to this path and the many people who have made it possible. Thank you to each and every one of you as this would not have been possible without you.

My most sincere gratitude, I really don’t have a way to thank you for all you did for me.

Life is not easy for any of us. But what of that? We must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something and that this thing must be attained.

Marie Curie

DECLARATION FORM

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ABSTRACT

Access to renewable energy supplies is a critical foundation for sustainable development and poverty alleviation. Anaerobic biogas-digesters also referred to as bio-digesters, have been identified as one of the leading technologies with regards to assisting in improving energy access for remote rural areas that still remain dependent upon biomass usage. This thesis assesses the potential feasibility of bio-digesters for rural households in South Africa by focusing on the experiences of a remote and rural community in Eastern Cape. A standardised survey was used to capture household details and energy use patterns of households with 180 interviews being conducted. Field observations were also conducted on the five bio-digesters installed in the community over a three month period. Despite the predominance of electrification in the community, households were heavily reliant upon biomass in the form of fuelwood and cattle dung to supplement their energy needs. Households supplemented their energy usage with alternative energy sources such as LPG gas and paraffin, especially during periods when electricity was unavailable or deemed too expensive. Initial knowledge of bio-digester technology in the community was non-existent, however with the installation of bio-digesters within the targeted villages, social learning was observed. Despite low temperatures bio-digesters continued to function throughout the study period, though malfunctions did occur and gas production did not reach optimal levels. Primary challenges encountered were the lack of financial subsidies for wide-spread adoption; the limited technical capacity of the community to conduct repairs and minimal gas production due to a build-up of ligneous materials within the gas chamber of the bio-digesters. Bio-digesters were found to provide significant benefits for households and further studies into maximising their effectiveness for rural South African households are recommended.

ACKNOWLEDGEMENTS

I would like to thank Professor James Gambiza for his constant support and encouragement during the course of this study, and over the many years that he has encouraged me to pursue my research interests. For the intellectual freedom that accompanied that support, I will always be grateful.

Funding received from a number of sources allowed me to focus full time on this study, and of that privilege, I am very conscious. The research in this project was funded by the Water Research Commission (WRC - Project Number K5/1955). I am sincerely grateful to the WRC for making this project a possibility.

Thank you to the community members in Machubeni, for your interest and enthusiasm throughout the project and welcoming me into your homes. Especial mention for 'Mama Florence' who went above and beyond to make me feel at home. To the consultants, government officials and other stakeholders in each of the sites, thank you for opening up your processes to an outsider, and allowing me to listen. To my mother, Jhan, thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 : INTRODUCTION AND CONCEPTUAL OVERVIEW

1.1 The relevance and importance of biogas as a renewable energy source

In September 2000, world leaders at the United Nations Millennium Summit agreed to a set of time-bound and measurable goals in order to combat poverty, hunger, illiteracy, gender inequality, disease and environmental degradation (ESCAP 2011). These goals came to be known as the Millennium Development Goals (MDGs), and in order to achieve them, significant progress in improving equitable access to energy resources needs to take place. The importance of energy access was first officially recognised at the World Summit on Sustainable Development in Johannesburg in 2002 and has become a recurring theme in much of the available literature dealing with renewable energy (Holm-Nielsen et al. 2009, AGECC 2010, Chen et al. 2010, Bruce et al. 2011, Martinot 2013). This energy challenge has been compounded by the elevated levels of greenhouse gas emissions, with the global total having recently passed 400 parts per million of atmospheric carbon dioxide (Allen et al. 2014). This has grave implications for global climate change and could potentially trigger a warming of 2°C when compared with pre-industrial levels (Martinot 2013). Therefore, in order to meet the growing energy needs in a climate-constrained world, we need to reassess how energy services are to be delivered in the future.

As of September 2015, the United Nations unanimously adopted a new set of Sustainable Development Goals (SDGs) at the United Nations Sustainability Summit. The SDGs build upon the MDGs and incorporate a total of 17 goals with 169 specific targets (Figure 1-1). Of particular significance is goal seven, 'Renewable Energy' which specifically outlines the importance of universal access to affordable, reliable and modern energy services. The aim is to substantially increase the use of renewable energy globally and double the global rate of improvement in energy efficiency by 2030.

Figure 1-1 The 17 Sustainable Development Goals (UNSDG 2015).

Overall the SDGs aim to replicate and improve upon the successes that the MDGs have achieved over the past 15 years with a particular emphasis on balancing the social, economic and environmental variables. Griggs et al. (2013) elaborate upon the revaluation of how we conceptualise the three pillars of sustainable development with society and economy nested within the environmental sphere (Figure 1-2). This model promotes the definition of sustainable development as being "*Development that meets the needs of the present while safeguarding Earth's life-support system, on which the welfare of current and future generations depends*" (Griggs et al. 2013). This definition reinforces the importance of renewable energy as a component of sustainable development and aims to minimise anthropogenic damage to our fragile ecosystem.

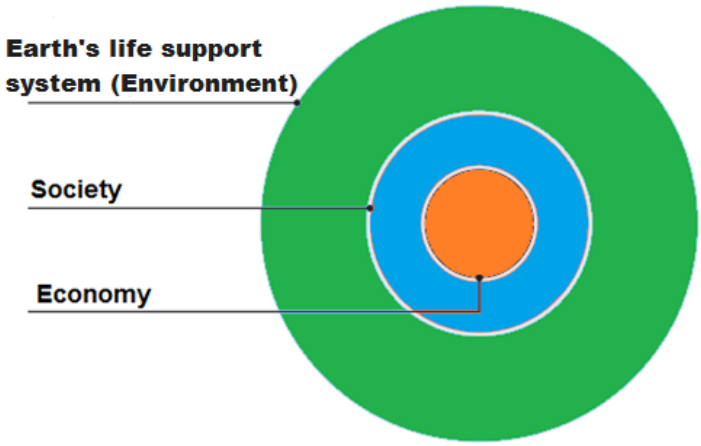

Figure 1-2 Society and economy nested within the earths support system (Adapted from Griggs et al. 2013).

1.2 Worldwide biomass usage

Worldwide, roughly 1.3 billion people continue to lack access to electricity and 2.6 billion rely on biomass fuels including wood, dung, agricultural residues and coal to supply their energy needs (Martinot 2013). Over 99% of these people live in developing regions, with four out of five living in rural South Asia and Sub-Saharan Africa (Brew-Hammond 2010). Whilst these low-cost biomass energy sources have managed to sustain the livelihoods of communities in the past, the tipping point with regard to environmental degradation is quickly becoming apparent as our utilisation of these natural resources outstrips the natural replenishment rate (Scheffer 2010).

The over-dependence on wood fuels has accelerated deforestation and contributed to the emission of greenhouse gases worldwide (Shackleton et al. 2007a). Trees perform a critical function in the ecosystem by improving air quality, conserving water, preserving soil structure, regulating temperature, supporting wildlife, and playing a role in wide-scale climate amelioration (Madubansi & Shackleton 2006). The accelerating deforestation of Africa due to increased demand for fuel has resulted in stored carbon being released back into the atmosphere at an alarming rate with future predictions estimating up to seven billion tons of carbon being released into the atmosphere by Africa alone by 2050 (KITE 2008, Ciais et al. 2011). The importance of rectifying this problem is compounded by the fact that use of biomass as a fuel has a direct negative impact on human health due to indoor

smoke inhalation. Gwavuya et al. (2012) highlighted the manner in which the inefficient use of biomass as a fuel in rural households was linked to respiratory diseases resulting in as many as 1.3 million deaths annually.

The socio-economics of rural households directly impacts upon the choices that they make in their interactions with regards their energy sources with their inability to afford more efficient energy sources limiting many households' choices. There are well-established links between increasing levels of wealth and their effects on biomass usage. Trends indicate that as the per capita income increases, traditional, or biomass, fuel usage decreases (Figure 1-3). This is accompanied by a pattern of rising energy consumption with wealthier households consuming more varied energy sources (Eckholm 1975, Hiemstra-van der Horst & Hovorka 2009). Low-income households have a strong incentive to minimize fuel expense and reduce the consumption of more expensive, high-quality fuels rather than that of cheaper, low-quality fuels.

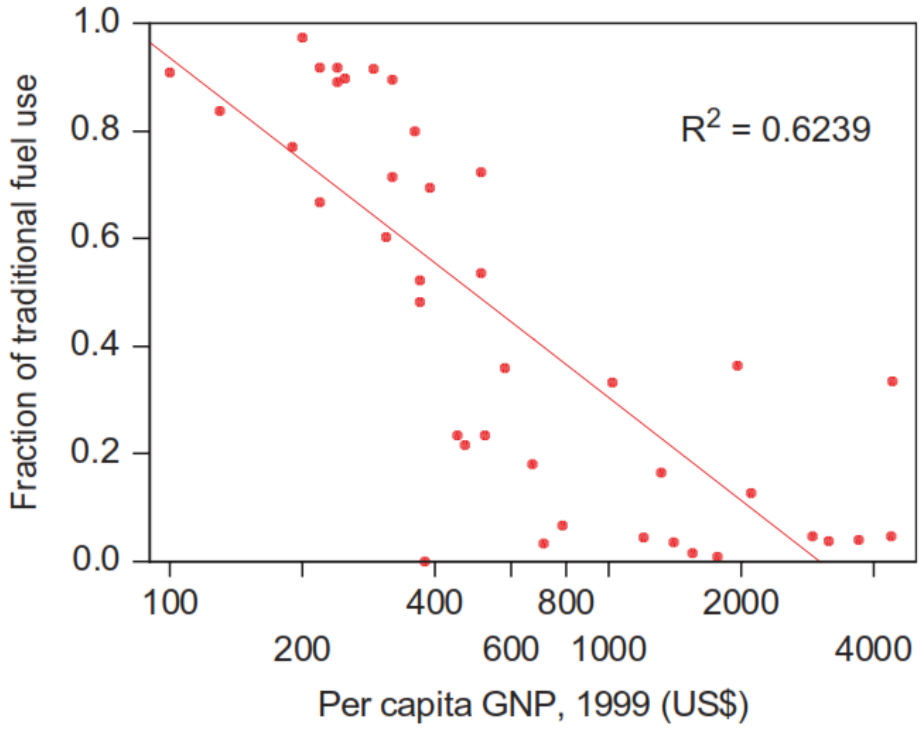

Figure 1-3 Relationship between per capita GNP and fraction of the population using 'traditional' fuels (Adapted from Smith et al. 2004).

1.3 Biogas as an alternative energy source

Biogas technology has been established as a mature and well-suited renewable energy source which has great potential in delivering a sustainable solution to the issue of energy access (ISAT/GTZ 1999a, Brew-Hammond 2010, Amigun et al. 2011, Ishola et al. 2013). Biogas offers a suite of benefits at various scales in a decentralised manner and directly assists in poverty alleviation due to the readily available nature of its primary inputs (Amigun & Blottnitz 2007, Renwick et al. 2007, Holm-Nielsen et al. 2009, Yu et al. 2008).

Austin and Blignaut (2008) highlighted many social, economic and environmental benefits that are directly and indirectly associated with the establishment of a national programme for the implementation of bio-digesters, also known as biogas-digesters, in South Africa. Their study found a potential for household bio-digesters in 310 000 households in six provinces in South Africa. The numerous benefits and opportunities highlighted in this report generated sufficient interest and funding for a five-year project which was initiated by the Water Research Commission (WRC) in 2009.

In April 2010 AGAMA Energy, the University of KwaZulu-Natal and Rhodes University initiated a project to assess the benefits and impacts on rural livelihoods, grasslands and animal health that are related to the use of bio-digesters and rainwater harvesting systems. Within this five-year project, AGAMA Energy installed 12 bio-digesters for selected households in KwaZulu-Natal and the Eastern Cape.

This study builds on the goals set out for this project with the intent of increasing our understanding of the application of this technology in a rural South African setting.

1.4 Aim and objective

The aim of this research was to assess the suitability and potential benefits of biogas technology in rural communities in the Eastern Cape, South Africa.

1.5 Key questions

Key questions which this study attempted to answer were as follows:

1. What potential benefits do bio-fuels provide to rural households?
2. What is the current energy profile of rural households?
3. What are the perceptions and experiences of biogas users in rural households?
4. What are the operational challenges facing biogas development and usage in rural households?

1.6 Structure

The thesis is structured as follows:

Chapter 1 introduces the research problem and the rationale which motivated the study, highlighting renewable energy's role in achieving the Sustainable Development Goals. The concept of sustainable developmental goals is expanded upon and the worldwide reliance on wood as a primary rural fuel source unpacked. The option of using biogas technology as an alternative renewable energy source is briefly outlined, and finally the aim of this study, and its key questions are presented.

Chapter 2 reviews the literature by broadening the theoretical background, outlining the general mechanics of bio-digesters and the chemical processes of bio-digestion, and presents a brief history of the use of bio-digesters. Key question one, regarding the potential benefits of biogas, is addressed within this chapter, through the use of examples from the literature. Additionally, the focus is narrowed towards past and current biogas projects within Sub-Saharan Africa, with a particular focus on developments in South Africa. Potential concerns regarding biogas development are raised and mitigation strategies discussed.

Chapter 3 introduces the study site and addresses the second key question, regarding the energy profiles of households in the study area. This chapter presents the data from the initial investigative survey and highlights energy use trends found.

Chapter 4 addresses key questions three, focusing on the changing perceptions of households in the study area and the role that social learning is playing with regards to dissemination of biogas knowledge. This chapter also presents its results and discussion in a paper format. The importance of social learning and community engagement are emphasised and discussed throughout this chapter.

Chapter 5 seeks to answer the final research question, regarding the operational challenges facing biogas development and usage in rural households. This chapter is also prepared in paper format and aims to assist in refining future policies regarding household bio-digesters. Major challenges and barriers are identified and discussed in length and possible mitigation strategies discussed.

Chapter 6 consists of a concluding discussion centred on the study's findings as a whole and discusses the overall suitability of biogas technologies for rural households in South Africa.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Biogas is a clean, efficient and quick-burning flammable gas which has been adopted worldwide to augment other more conventional renewable energy sources, such as solar power and hydroelectric power (Amigun & Blottnitz 2007, Renwick et al. 2007, Holm-Nielsen et al. 2009, Yu et al. 2008). It burns efficiently with a clean blue flame, leaving no soot or particulate, in a manner similar to LPG (liquefied petroleum gas), and releases minimal carbon dioxide into the atmosphere due to its short carbon chain length (ISAT/GTZ 1999a). Biogas is produced through the anaerobic fermentation of organic material, referred to as feedstock, in a sealed anaerobic environment called a bioreactor or bio-digester. After anaerobic digestion two outputs are generated, both biogas (which consists primarily of methane and carbon dioxide) and a nutrient rich slurry (Figure 2-1).

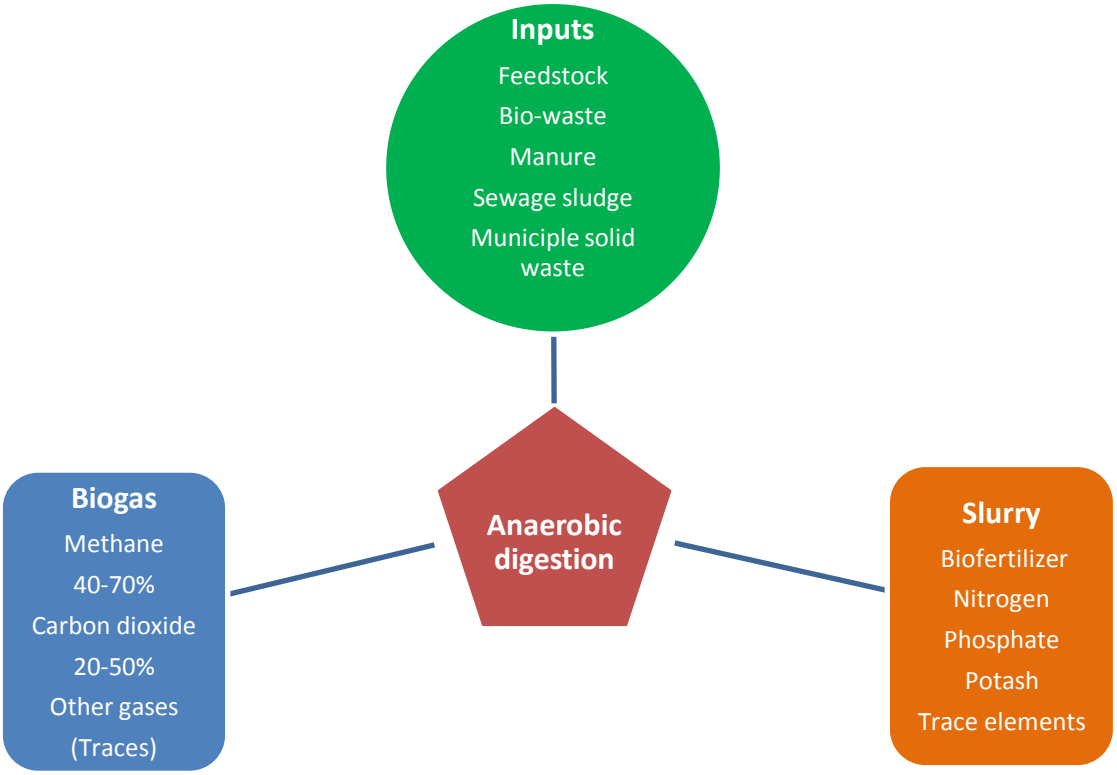

Figure 2-1: The bio-digester process (Adapted from ISAT/GTZ 1999a).

In addition to the biogas, a slurry is also produced which has the potential to assist in improving crop production and ensuring that nutrients are cycled back into the soil (Chen 1997, Zhou & Lin 2004, Gao et al. 2006, Xiaohua et al. 2007). Biogas is approximately 40 to 70% methane with the remainder of its volume consisting of carbon dioxide, water vapour, hydrogen sulphide and other trace gases (Sibisi & Green 2005, Lukehurst et al. 2010, Arthur et al. 2011, Abbasi et al. 2012). The high degree of variation in its composition is due to numerous variables such as the calorific value of the feedstock used, the retention time of the bio-digester and its total volume as well as environmental factors such as the ambient temperature of the bio-digesters (Bond & Templeton 2011). Anaerobic bio-digesters which are intended for household level installations are typically designed to operate under mesophilic conditions (20–40°C) and are best suited to temperature zones with minimal temperature variation (Bond & Templeton 2011, Amigun et al. 2011, Abbasi & Abbasi 2012).

Anaerobic bio-digesters have been identified as one of the leading technologies assisting in improving energy access for remote rural areas that still remain dependent upon biomass usage (Bond & Templeton 2011). The potential benefits of this technology are well documented, especially in Asian countries such as China and India, where it has been implemented on a massive scale in an effort to assist in poverty alleviation and rapid rural development (Gautam et al. 2009, Chen et al. 2010, Rao et al. 2010, Gwavuya et al. 2012, Poeschl et al. 2012a). Countries which rely heavily on biomass to fulfil their energy needs stand to benefit significantly due to the time savings and ease of use which the technology offers.

2.2 Types of bio-digesters

There are a variety of bio-digester designs which have been tested in order to maximise the efficiency and operational ease of biogas production (Hilkiah Igoni et al. 2008). These can be separated into three main categories: fixed dome digesters, floating cover digesters and balloon digesters, each with its advantages and disadvantages (Figure 2-2).
They can be scaled to a variety of sizes, with an average volume of 2 m^3 to 10 m^3 and biogas production of approximately 0.5 m^3 biogas per m^3 of bio-digester volume (Akinbami et al. 2001, Omer & Fadalla 2003).

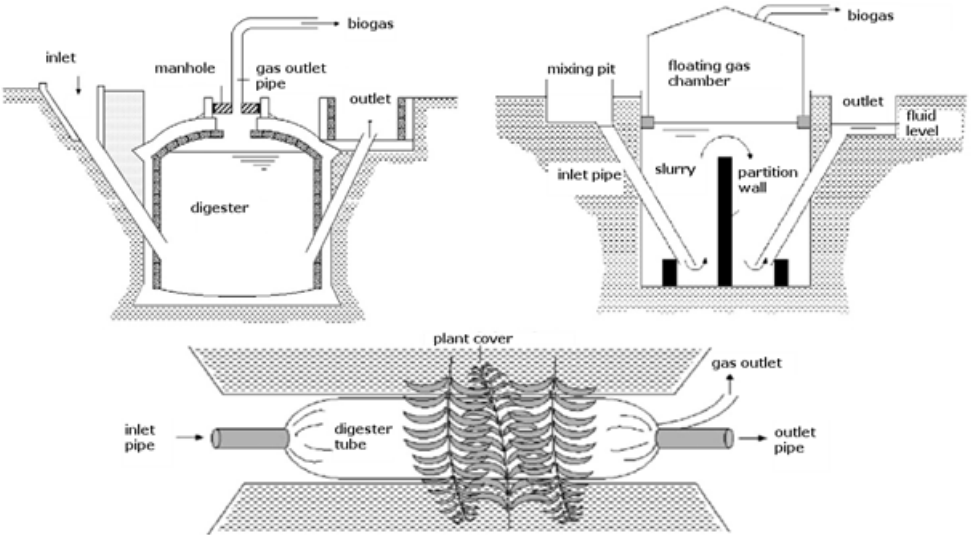

Figure 2-2: Common bio-digester designs in the developing world. Top left: fixed dome digester (Chinese type). Top right: floating cover digester (Indian type). Bottom: Balloon digester (Adapted from Bond & Templeton 2011).

2.2.1 Fixed dome bio-digesters

Fixed-dome bio-digesters consist of an immobile gas holder, which rests above the bio-digester. These bio-digesters are usually constructed from robust materials such as bricks or concrete, but can also be fabricated out of hard wearing plastics. The slurry is displaced as gas production starts, forcing it into the outlet trough (Brew-Hammond 2010). Gas pressure increases with the volume of gas stored and the slurry returns to the reactor chamber as gas is used. The relatively low construction costs, coupled with no moving or corrodible parts, are some of the major advantages of this system (ISAT/GTZ 1999a, Bond & Templeton 2011). When insulated underground, these bio-digesters take up little space and are able to continue operating under lower temperature conditions than other designs. Major disadvantages of the design are the stringent construction standards which must be followed in order to achieve a gas-tight fitting, as well as gas pressure fluctuations according to the volume of gas available, which can lead to complications if the bio-digester is not directly adjacent to the gas appliance(ISAT/GTZ 1999a, Austin & Morris 2012).

2.2.2 Floating drum bio-digesters

Floating drum digesters are also generally constructed underground in order to save space and are very similar to fixed dome digesters in shape (Bond & Templeton 2011). The primary difference is the moving gas-chamber, which floats either directly upon the slurry in the reaction chamber, or upon a separate water jacket (Austin & Morris 2012). As the gas accumulates, the chamber moves up along a guiding frame, allowing excess gas to escape once the chamber is at maximum capacity. The constant gas pressures, alongside a clear visual indicator as to how much gas is available, are two of the biggest advantages of this design (ISAT/GTZ 1999a). Construction is simpler than the construction of fixed-dome bio-digesters, with a greater tolerance for error. Major disadvantages of the design include the relatively high cost of the steel drum, which serves as the gas chamber, in addition to its susceptibility to corrosion leading to a shorter lifespan than a fixed-dome bio-digester (Nzila et al. 2012).

2.2.3 Balloon bio-digesters

The simplest design is the balloon bio-digester, which consists solely of an airtight bag with an inlet and outlet valve (Nzila et al. 2012). Gas pressure is achieved through the elasticity of the bag material, and can be increased through the use of weights added onto the balloon (ISAT/GTZ 1999a). The advantages of these simple bio-digesters are their low cost, ease of transport and ease of maintenance due to having no moving parts. Their disadvantages arise from their fragility, and they thus have the shortest lifespan relative to the other designs, with even a small tear greatly diminishing the efficiency of the bio-digester (Nzila et al. 2012). In addition, the design has little to no insulation and is susceptible to break down in both low and high temperatures, limiting its effectiveness in many geographical locations (Bond & Templeton 2011).

2.3 Chemical processes of anaerobic digestion

The process of anaerobic digestion begins with extracellular enzymes degrading complex carbohydrates, proteins and lipids into their constituent units (Figure 2-3)(Balmant et al. 2014). The large protein macromolecules, fats, and carbohydrate polymers (such as cellulose and starch) are cracked into water-soluble monomers (amino acids, long-chain

fatty acids, and sugars). This occurs due to hydrolase enzymes present in facultative and obligatory anaerobic bacteria. This is followed by acidogenesis, which involves the conversion of hydrolysis products into 'volatile fatty' acids, such as lactic propiotic, butyric and valeric acids (Bond & Templeton 2011). These are then consumed by homoacetogenic microorganisms in a process called acetogenesis which produces the acetic acid, carbon dioxide and hydrogen (Abbasi et al. 2012). The final stage of bio-digestion is methanogenesis, where anaerobic micro-organisms consume the acetate, hydrogen, and some of the carbon dioxide in order to produce methane (Bond & Templeton 2011, Abbasi et al. 2012).

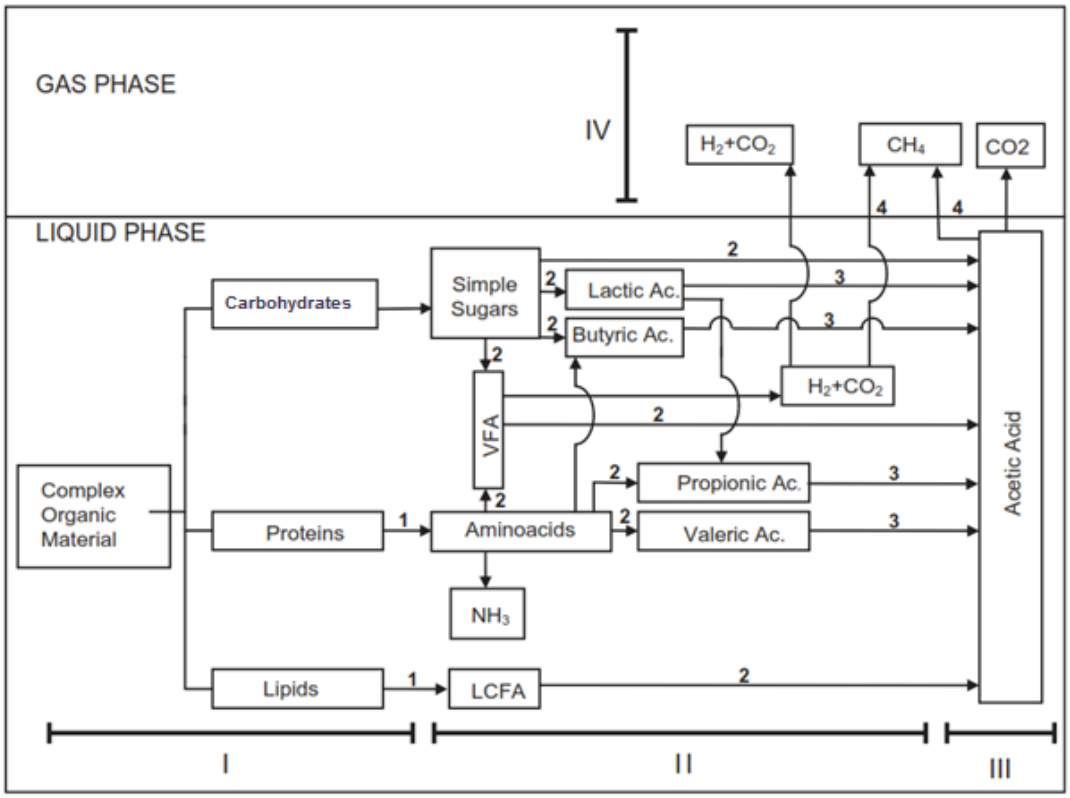

Figure 2-3: Four steps of the anaerobic digestion system: I) Hydrolysis; II) Acidogenesis; III) Acetogenesis; IV) Methanogenesis Microbial groups (Adapted from Balmant et al. 2014).

In theory, biogas should contain equal volumes of methane and carbon dioxide. Acetogenesis, however, typically produces some hydrogen (Avery et al. 2014). For every four moles of hydrogen consumed by hydrogenotrophic methanogens, a mole of carbon dioxide is converted to methane (Abbasi et al. 2012).

Fats and proteins can yield larger amounts of hydrogen leading to higher typical methane content for these substrates, therefore, the overall biogas yield and methane content varies for different feedstock due to disparities in calorific value (Bond & Templeton 2011, Naik et al. 2014).

2.4 History of biogas

It has been suggested that biogas usage goes back as far as the 10th century B.C., where it was apparently used for heating bath water in Assyria and in ancient China (He 2010). For the purposes of this study, we will be focusing on attempts to harness the anaerobic digestion of biomass from the mid-19th century.
Some of the very first recorded bio-digesters were constructed in New Zealand and India in the 1890s (Bond & Templeton 2011). These pioneering bio-digesters were used to fuel streetlights and were replicated in Europe, such as Germany. The adoption of this technology, however, only really gained momentum in the 1970s as oil prices rose and motivated research into alternative energy (ISAT/GTZ 1999a).

During the 1970s, the Chinese government embarked upon a massive rural development project promoting the use of biogas for every rural family. This resulted in the installation of over seven million bio-digesters in the late 1970s (He 2010). This trend has only been accelerated since the turn of this century, and in 2007 there were 26 million bio-digesters operating in China, making them the world leaders in household biogas development (Chen et al. 2010). Biogas has thus managed to contribute significantly towards sustainability, with 832,749 TJ of biogas energy provided for cooking, lighting, water pumping and other power applications over the past 15 years (Yu et al. 2008). India has also managed to tap into its massive biogas potential and establish a nationwide implementation plan with approximately 4.5 million bio-digesters being installed as of 2012 (Rao et al. 2010).
This is an on-going process and it is believed that only a third of the country's true biogas potential (Pohekar et al. 2005).

2.5 Potential benefits of biogas

2.5.1 Millennium Development Goals

Biogas technology can also assist in the achievement of the Millennium Development Goals, which are internationally recognised targets regarding the alleviation of poverty and improvement of human well-being (ESCAP 2011). By providing rural households with a low cost, minimal maintenance sanitation device that also assists in providing energy, the achievement of these goals in the prescribed time limit becomes more realistic (Table 2.1.)

Table 2-1 Biogas contribution to the MDGs (ESCAP 2011).

Millennium Development Goal	UNDP Findings
1. End poverty and hunger	Reduced time lost gathering wood, increased the time available for other productive activities. Food can be cooked safely.
2. Universal education	Less time spent collecting wood means more time for education.
3. Gender equality	Reduced burden on women to obtain cooking fuels.
4. Child health	Reduction in smoke inhalation-related diseases among young children. Reduction in cold-related diseases among young children.
5. Maternal health	Increased birth weight of children without smoke. Hot water available, essential for childbirth. Improved comfort and health of the mother in pregnancy and childbirth.
7. Environmental sustainability	Improved practices reduce deforestation and emissions.

2.5.2 Sustainable Development Goals

As of September 2015, a new set of goals has been unanimously adopted at the United Nations Sustainability Summit by the United Nations (UNSDG 2015). The Sustainable Development Goals (SDGS) build upon the MDGs and incorporate a total of 17 goals with 169 specific targets (Figure 1-1: Chapter 1) Of particular significance is goal seven, 'Renewable Energy' which specifically outlines the importance of universal access to affordable, reliable and modern energy services.

The aim is to substantially increase the use of renewable energy globally and double the global rate of improvement in energy efficiency by 2030 (UNSDG 2015).Overall the SDGs aim to replicate and improve upon the successes that the MDGs have achieved over the past 15 years with a particular emphasis on balancing the social, economic and environmental variables.

2.5.3 Greenhouse gas mitigation

When organic matter such as food, plant debris, animal manure, sewage sludge and biodegradable portions of solid waste undergoes decomposition in the absence of oxygen, it naturally produces methane. Methane is considered a powerful greenhouse gas, with each molecule responsible for about 25 times more global warming than an equivalent carbon dioxide molecule (Abbassi-Guendouz et al. 2013). Thus, if we do not process organic waste and instead allow it to rot in the open, we are indirectly contributing towards the proliferation of greenhouse gases. There are many different waste streams which contribute to this problem such as dung, the biodegradable part of untreated municipal solid waste, dead plants decaying at the bottom of lakes and ponds, human excreta or sewage, tanneries, distilleries and other industrial discharge (Walekhwa et al. 2009, Abbasi et al. 2012). The microbial-controlled production of biogas is an important part of the global carbon cycle and has a significant impact on the overall composition of greenhouse gases in the atmosphere (Kossmann et al. 1997).

Every year the natural biodegradation of organic matter under anaerobic conditions is estimated to release 590 to 800 million tons of methane into the atmosphere (Kossmann et al. 1997). The use of biogas technology as a recovery system assists in the disposal of these ‘waste’ biomass streams in a manner which also provides renewable energy (Bond & Templeton 2011). In this way, we are able to minimise our contribution to anthropogenic greenhouse gases whilst simultaneously assisting in poverty reduction (Austin & Morris 2012).

2.5.4 Rural household energy access

It was noted earlier that the low energy access rates in Sub-Saharan Africa are correlated with challenges in meeting one or more of the MDGs, including the goal of eradicating

poverty (ESCAP 2011). Lack of energy access contributes directly to this by degrading people's ability to meet their basic physiological needs and by disrupting energy's contribution to basic education, health care and the ability to work (Gosens et al. 2013). Unlike other forms of renewable energy, biogas production systems are relatively simple and can operate at small and large scales in both urban and very remote rural locations (i.e. there are no geographical limitations to the employment of this technology, and it is not monopolistic) (Amigun & Blottnitz 2007). Bio-digesters can be implemented at both the household and village-scale by simply increasing the number of bio-digesters in a parallel configuration. Once the production of biogas reaches significant volumes, it is even possible to generate electricity via the use of fuel cells or modified generators (ISAT/GTZ 1999a).

2.5.5 Reduced pressure on natural fuelwood reserves harvested by rural households

The installation of bio-digesters has been proven to have a significant impact upon fuelwood use in households, with Nepalese households reporting up to two tons of fuelwood being saved annually (Gautam et al. 2009). In Ethiopia, it has been estimated that households could reduce their fuelwood usage by up to two tons annually, depending upon the size of their bio-digester (Gwavuya et al. 2012). This reduction of fuelwood harvesting has numerous indirect benefits to ecosystem health and human livelihoods especially in areas which are heavily reliant upon their natural resources to supplement their socio-economic development (Shackleton et al. 2007b)

2.5.6 Improving food security of rural households

Food security is one of the most contentious points when discussing the expansion of bio-fuels into African countries, due to severe negative impacts on natural biodiversity and increased competition over limited land and water resources (Janssen & Rutz 2012). Possible increased prices, as well as conflict over land ownership and displacement of rural communities, have also been identified as areas of concern, especially with regard to large-scale bioenergy projects (Escobar et al. 2009).

These concerns, however, do not apply to the use of domestic bio-digesters as their primary feedstock is derived from materials which are often considered to be a 'waste stream'. The use of bio-digesters assists in nutrient cycling by preventing the burning of crop residues and animal dung as an energy source, thereby ensuring that potentially lost nutrients are returned to the soil (Gwavuya et al. 2012). The bio-slurry that is produced by the bio-digester acts as a fertiliser, potentially replacing commercial fertiliser and increasing yields. This enhances food security for rural households (Chen et al. 2010, Orskov et al. 2014, Chodkowska-Miszczuk & Szymańska 2013).

2.5.7 Promoting gender equality within rural households

Another significant benefit of this technology is the manner in which it serves to promote gender equality and free up significant amounts of time for women in rural households, who are traditionally responsible for collecting fuelwood, as well as cooking meals (Karekezi 2002, Katuwal & Bohara 2009, Arthur et al. 2011). This is especially important in Sub-Saharan Africa, where female-headed households are far more common than in other developing regions (Blackden & Wodon 2006).

2.5.8 Health benefits with regards to sanitation and air quality improvements

One final major benefit which biogas production provides is a simple means to reduce the health risks associated with hazardous indoor air pollution as well as improving the general health of households due to improved sanitation. Whilst the anaerobic digestion process does not kill all pathogens, it has had a significant impact on the health of households which have had it installed (Gautam et al. 2009, Bond & Templeton 2011, Gwavuya et al. 2012, Huong et al. 2014, Smith et al. 2015).

2.6 Availability of feedstock and scalability

One of the key advantages of bio-digesters is that feedstock material is readily available in rural areas with livestock manure, kitchen scraps or even crop residues, which are all easily digested. Due to the modular nature of biogas digesters, they are uniquely suited towards assisting development within African countries, especially within more remote areas (Amigun & Blottnitz 2007, Renwick et al. 2007, Hiemstra-van der Horst & Hovorka 2009, Amigun et al. 2011, Nahman et al. 2012).

Scaling up production can be accomplished through the addition of bio-digesters in a parallel configuration, allowing for implementation at both household and village-scale with minimal design changes.

2.7 Established pitfalls and challenges of biogas implementation

The technological capacity, socio-political stability, and economic viability of biogas technology are all critical to the successful implementation of biogas (Figure 2-4). These factors will be briefly discussed drawing upon examples around the world.

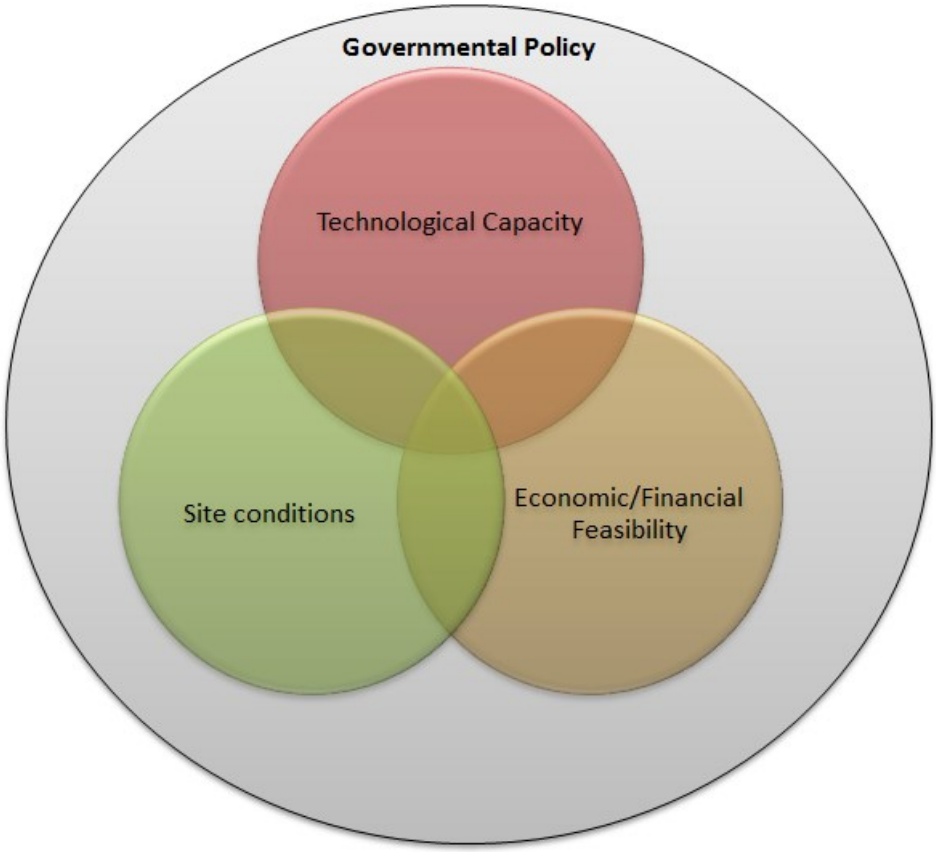

Figure 2-4: Interlinking factors influencing successful implementation of biogas technologies (Adapted from Barry et al. 2011).

2.8 The role of governmental policy for biogas technology adoption

Clear and cohesive governmental renewable energy policies have a huge role to play with regards to ensuring that new technologies are implemented correctly. Establishing clear targets with adequate scope for expansion is one of the first steps towards creating a viable

renewable energy policy. Additionally sustainable financing needs to be secured to ensure the stability required for a decentralised household biogas programme to flourish (Msimanga & Sebitosi 2014).

These basic policy frameworks are critical components required to achieve the critical mass of technical skills and invested capital required for rapid implementation. It can, therefore, be said that African countries aiming to succeed in implementing biogas strategies must first focus on developing innovative and transparent policy frameworks (Mwirigi et al. 2009). Some progress has been made in this regard by the Forum of Energy Ministers of Africa (FEMA) as well as between several other regional African economic communities (ABPP 2014). Specific energy targets and policies aiming to increase energy access are slowly becoming more common (Modi et al. 2005). One of the most promising initiatives currently making great progress has been 'The Africa Biogas Partnership Programme' (ABPP). This partnership between two global NGOs (Hivos and the SVN) and five African countries (Kenya, Burkina Faso, Ethiopia, Uganda and Tanzania) aims to support the national programmes of each country and install 100 000 bio-digesters by 2017 (ABPP 2014). Currently, over 32 075 have been installed with the majority being installed in Kenya where it is quickly becoming more popular and accepted in rural areas (Ghimire 2013, ABPP 2014).

2.8.1 South African national policy regarding biogas implementation

Understanding South Africa's current energy policies requires a brief overview of the details surrounding its energy sector. Eskom, a state-owned enterprise, generates 95% of all electricity used in South Africa and accounts for approximately 45% of all electricity generated on the continent (Eskom 2014). Over 80% of this electricity is generated through the exploitation of South Africa's extensive coal reserves (estimated at 50 billion tonnes) (Sebitosi 2010, Eskom 2014).

This has led to South Africa contributing approximately 511 million tonnes of CO_2 into the atmosphere, resulting in the country being considered the twelfth highest emitter in the world. With an estimated per capita emission of 9.18 tonnes, it can be seen that South Africa is exceeding the global average of 4.49 tonnes per capita (Urbanearth 2012). South Africa is therefore faced with a challenging prospect of creating policies which both

minimise the substantial carbon footprint and do so in a financially viable manner. Decades of access to 'cheap' coal has stunted the growth of the renewable energy sector, and the consolidation of both power generation and distribution within a single company has resulted in the government being heavily reliant upon Eskom to supply all energy needs(Urbanearth 2012). This has resulted in a feed-in tariff system being adopted, whereby potential power providers must bid against each other for government-sanctioned contracts with fixed tariff rates over a long term period (Fritz 2012).

Eskom is compelled to purchase a set amount of power from whichever provider wins any given contract and, hypothetically, the renewable energy goals set out in 2003 by the White Paper on Renewable Energy can be achieved (Pegels 2010, Fritz 2012). While provision is made in this legislative framework for small to mid-level developments such as bio-digesters, no comprehensive implementation strategy, such as the ABPP, has been officially adopted. This form of policy is directly contrasted with the subsidy model adopted throughout Asia, where countries such as Nepal, India and China empowered rural households by allocating significant subsidies for the construction of bio-digesters (Amigun & Blottnitz 2007, Gautam et al. 2009, Griggs et al. 2013, Sun et al. 2014, Sebitosi 2010, Msimanga & Sebitosi 2014). In spite of the lack of overarching governmental policy and funding, the bio-digesters installed at Machubeni were installed as part of an overarching research project by the Water Research Commission (Project K5/1955). The results of this five-year study will, therefore, feed into a further discussion regarding future implementation policies for biogas in South Africa.

2.8.2 Municipal interest and participation in biogas implementation

Currently, municipalities are unable to engage directly with independent power providers and off-grid projects. Household biogas generation, for example, is not eligible for governmental support (Msimanga & Sebitosi 2014). Municipalities are therefore forced to operate in a relative vacuum with regard to micro-scale programmes such as household bio-digester construction. This is a major barrier and completely contrary to the kinds of policies being adopted in other developing countries (Akinbami et al. 2001, Coelho & Goldemberg 2013, Ghimire 2013, Sun et al. 2014).

2.9 Technological challenges for biogas implementation

Ensuring that the bio-digesters are capable of delivering sufficient flammable gas for daily cooking is the critical factor in determining the household's adoption of the technology and ensuring that they do not simply revert to their previous fuel sources (Barry et al. 2011, Brew-Hammond 2010, Bruce et al. 2011). In South East Asia the standardisation of the various biogas components assisted immensely in ensuring that competing companies were able to work together under a single umbrella of established quality.
This led to improved quality control and assisted in the overview of installations on a macro level by allowing for more effective inspection of finished installations (Mwirigi et al. 2009).

2.9.1 Quality of biogas installations

Despite the simplicity of the technology and its minimal moving parts, quality control of installation is one of the most challenging aspects of any large-scale biogas project (Brew-Hammond 2010, Black et al. 2011, Bruce et al. 2011). One of the most common faults reported by biogas users is low pressure or reduced gas production. This is most often caused by a leak in either the gas chamber of the bio-digester or the pipes supplying the stove (Cheng et al. 2014). These leaks can be minimised through the use of prefabricated units, such as those installed in China. These prefabricated fixed dome digester types have become prevalent due to their robust design and minimal maintenance cycles (Cheng et al. 2013). These units experience fewer leaks, due to stricter factory quality control and careful testing of each bio-digester before it is installed two meters underground. The positioning of the units underground was done to assist in insulation for heat retention purposes as well as to minimise accidental damage to these airtight components (ISAT/GTZ 1999a, Oldfield 2012).

2.9.2 Peripheral devices

Due to the physiochemical properties of biogas, commercial butane and propane burners are not suitable for biogas without modification. Further, biogas is not an efficient source of lighting or heating due to the overall lower calorific value of biogas in comparison to butane, propane and other commercially available LPGs (ISAT/GTZ 1999a). Since six litres of air are required to combust one litre of biogas, commercial appliances require larger gas jets when

burning biogas (Bond & Templeton 2011). Stove design should accommodate various cooking implements such as the large cast iron pots which are often used by rural households.

2.9.3 Maintenance plans

Adequate user training and constant maintenance are critical factors when ensuring the sustainability and longevity of bio-digesters. Despite the simplicity and robust design of bio-digesters, leaks and malfunctions can arise between the outlet valve and the gas appliance. The technological capacity to repair or replace these gas lines and fittings are often sorely lacking at many installations (Amigun et al. 2011, Okello et al. 2013, Orskov et al. 2014). One of the major constraints encountered in implementing biogas technology in China was poor follow-up services and management of bio-digesters (Chen et al. 2010). Many farmers claimed to have received minimal training and had limited knowledge of how their bio-digesters actually worked (Jiang et al. 2011). Most farmers in rural China have little formal education, and most of them have no access to information about biogas energy. The majority of these farmers have not received adequate support and training in managing the bio-digesters and have not been introduced to safety procedures and management of the bio-digesters in addition to being unfamiliar with the construction of the system (Zhang et al. 2007). The lack of attention paid to bio-digester maintenance has been identified as a significant factor for failure while qualified technical support is in short supply.
Trends in determining bio-digester success appear to focus and emphasise the construction and commissioning of bio-digesters rather than the successful long-term operation and maintenance of bio-digesters (Chen et al. 2010).

2.10 Site Selection

2.10.1 Ambient temperature

One of the primary limitations of bio-digester technology is the ambient temperature of the bio-digester site, with lower ambient temperatures resulting in decreased biogas production (Harmon et al. 1993, El-Mashad et al. 2004, Bohn et al. 2007, Gao et al. 2012, Zhang et al. 2012, Chen et al. 2013, Kundu et al. 2013). Studies have determined that optimal operating temperatures for a bio-digester lie between 35°–40°C, however, bio-digesters continue to

operate at temperatures as low as 12°C (Khan et al. 2014). Therefore, there are many regions within South Africa where the ambient temperature is sufficient to maintain the fermentation process all year round and no artificial heating is required (Austin & Morris 2012).

2.10.2 Cultural preference of households

Regardless of the efficiency, ease of use and numerous other benefits associated with the technology, cultural preference remains an importance factor in biogas usage (Mwirigi et al. 2009, Msimanga & Sebitosi 2014). One example is the manner in which 'traditional' meals are considered to be more flavorful if cooked using certain fuelwoods (Akinbami et al. 2001). This directly influences the uptake of biogas technology as a complete replacement, with households preferring to simply add biogas to their existing energy profile, in the same way that electricity was incorporated (Madubansi & Shackleton 2006).

2.11 Economic and financial viability

Despite conditions appearing to be highly conducive towards its propagation, the growth of biogas technology in Africa has been a sluggish, fitful affair with numerous pilot projects being initiated and subsequently abandoned across the continent (Davis & Horvwi 1995, Jingura & Matengaifa 2009, Amigun & von Blottnitz 2010, Black et al. 2011, Brew-Hammond 2010, Ghimire 2013).

In order to better understand this, it is necessary to look at the economic and financial feasibility of the technology. Austin et al. (2008) provided South Africa with its first comprehensive biogas audit, highlighting the potential net benefits and opportunities that can be exploited through the implementation of the technology. A more focused study by Smith et al. (2014) evaluated the economic and financial feasibility of bio-digesters within a rural community in South Africa. These findings highlight the economic viability and financial feasibility of bio-digesters and are supported by additional literature (Renwick et al. 2007, Amigun & Blottnitz 2007, KITE 2008, Amigun et al. 2011, Msimanga & Sebitosi 2014, Orskov et al. 2014).

2.12 High initial investment costs

Whilst some of the above studies found biogas technologies more financially viable and sustainable than others, there is a consensus regarding the numerous economic benefits offered by biogas (ISAT/GTZ 1999b, Austin & Blignaut 2008, Gregory 2010, Khan et al. 2014). These studies also identify high initial investment costs as a significant barrier impeding the implementation of biogas technology.

Additionally, households are wary of the timescales involved with recouping these high costs (Jiang et al. 2011, Smith et al. 2014). This is especially true when considering projects on the African continent, where high initial investment costs are compounded by limited access to credit facilities (Orskov et al. 2014). This was mitigated in China through the implementation of biogas subsidies which required minimal screening and accounted for a large proportion of the total construction costs (Sun et al. 2014). This form of subsidy is not without its drawbacks, but it has significantly stimulated the uptake of bio-digesters and has created a sense of ownership within the households with installed bio-digesters. Evidence points to these farmers being sensitive to high initial costs and wary of long-term investments such as a bio-digester (Jiang et al. 2011).

2.13 Sustainability of biogas production

Numerous studies have been conducted into determining the most efficient and sustainable method of using biogas technology for the purposes of energy generation through the use of various methods such as: 'benefit to cost economic analysis' (Amigun & Blottnitz 2007, Braun 2010, Murphy et al. 2011, Yoshizaki et al. 2013) and 'environmental impact evaluation' (Poeschl et al. 2012b, Poeschl et al. 2012a, Börjesson & Berglund 2006, Patterson et al. 2011). However currently no single method has been widely adopted in order to describe and determine the sustainability of such projects (Wang *et al.* 2013). One universal factor is the size and number of the bio-digesters being installed, which is crucial when evaluating the overall sustainability of any biogas project. The 'energy return' of biogas is lower than traditional energy sources such as coal, natural gas and petroleum (Wang et al. 2013).

Financial costs of biogas and electricity from bio-digesters are higher than those of traditional energy, but this estimation is not inclusive of the overall cost when one considers the environmental costs which are often externalised by non-renewable energy generation, resulting in an artificially low cost that does not take into account the environmental costs associated with the generation of this energy (Holm et al. 2008).

Despite this, extensive research conducted by Wang et al. (2013) determined that large-scale biogas projects provide the extensive capacity to treat agricultural waste and produce renewable energy in an economically viable manner. One significant benefit that biogas and other renewable fuels have is the manner in which they are potentially carbon dioxide neutral (ISAT/GTZ 1999a). In other words, if carefully managed and properly implemented, minimal carbon dioxide is emitted through the use of these technologies. This serves as a strong argument in favour of renewable energies (Jury et al. 2010).

2.14 Conclusions

Biogas technology in the form of anaerobic bio-digesters has proven itself to be an effective development tool over the past few decades, with massive strides being taken in Asian countries. However, these successes have yet to be replicated in large-scale projects within the African continent. With an abundance of available feedstock, a burgeoning population and a crucial lack of energy access, Africa is currently in an ideal position to reap the benefits of this renewable energy source. However in order to effectively implement national level strategies, we will need to develop locally suitable implementation plans that are based upon experience. Data on the challenges faced by small-scale rural projects could be invaluable in assisting in the implementation of larger scale projects. By evaluating the rate of knowledge transfer amongst a community with little to no exposure to biogas we can more accurately model the adoption and likelihood of success of this renewable energy technology. This research aims to assist in closing the knowledge gap currently evident in the performance of bio-digesters in rural African households. It also aims to identify unique challenges and determine which experiences are universal to biogas technology in order to better facilitate its distribution.

CHAPTER 3 : CURRENT ENERGY PROFILE OF RURAL HOUSEHOLDS IN THE EASTERN CAPE

3.1 Introduction

Equitable and affordable access to energy are one of the fundamental pillars of sustainable development. With a burgeoning human population, set to rise to 9 billion by 2050, the widespread implementation of renewable energy is this century's greatest challenge if we are to achieve sustainable development.(Eisenberg & Nocera 2005, Modi et al. 2005, Godfray et al. 2010, Martinot 2013). However as outlined in Chapter 1, significant progress still needs to take place within the renewable energy sector, especially within developing countries. One possible solution with many benefits is the implementation of anaerobic bio-digesters which were covered in detail in Chapter 2. These bio-digesters provide numerous benefits for rural households in the Eastern Cape due to the manner in which they require minimal maintenance, use locally available materials for operation and assist in the expansion of energy options for these communities.

This research aims to assess the current energy profile of rural households within the Machubeni community, which lies in the Eastern Cape Province of South Africa.

3.2 Materials and methods

3.2.1 Study site

Machubeni (27°01–16'E; 31°27–36'S) is situated in the Eastern Cape Province, South Africa, and is approximately 40 km South West of Indwe and 20 km North of Lady Frere, which is the closest major town. The area is characterized by craggy and mountainous terrain, with the Stormberg Mountains to the north and the Mount Arthur Range to the South (Shackleton & Gambiza 2008). The terrain varies in height from approximately 1300 m above sea level (m.a.s.l.) to 2100 m.a.s.l. with villages found midslope at approximately 1500 m.a.s.l. Average annual rainfall is approximately 711 mm and is concentrated in the summer months between October and March. Rainfall is erratic and dominated by convective storms (Bolus 2009). The temperature ranges from a mean maximum of 12.5^{o}C in July to 20 ^{o}C in December (Bolus 2009).

Machubeni falls within the previous Bantustan territory known as the Transkei, which was considered an African homeland during the Apartheid era from 1976 until 1994 when it was reincorporated into South Africa (Figure 3-1). During this period, many South Africans were relocated to this area and restricted from moving out. With limited access to the rest of the country as well as minimal infrastructure and very little formal employment, the community has remained heavily reliant upon their limited natural resources, which contribute significantly to the welfare of rural households (Barrett et al. 2001, Shackleton & Gambiza 2008).

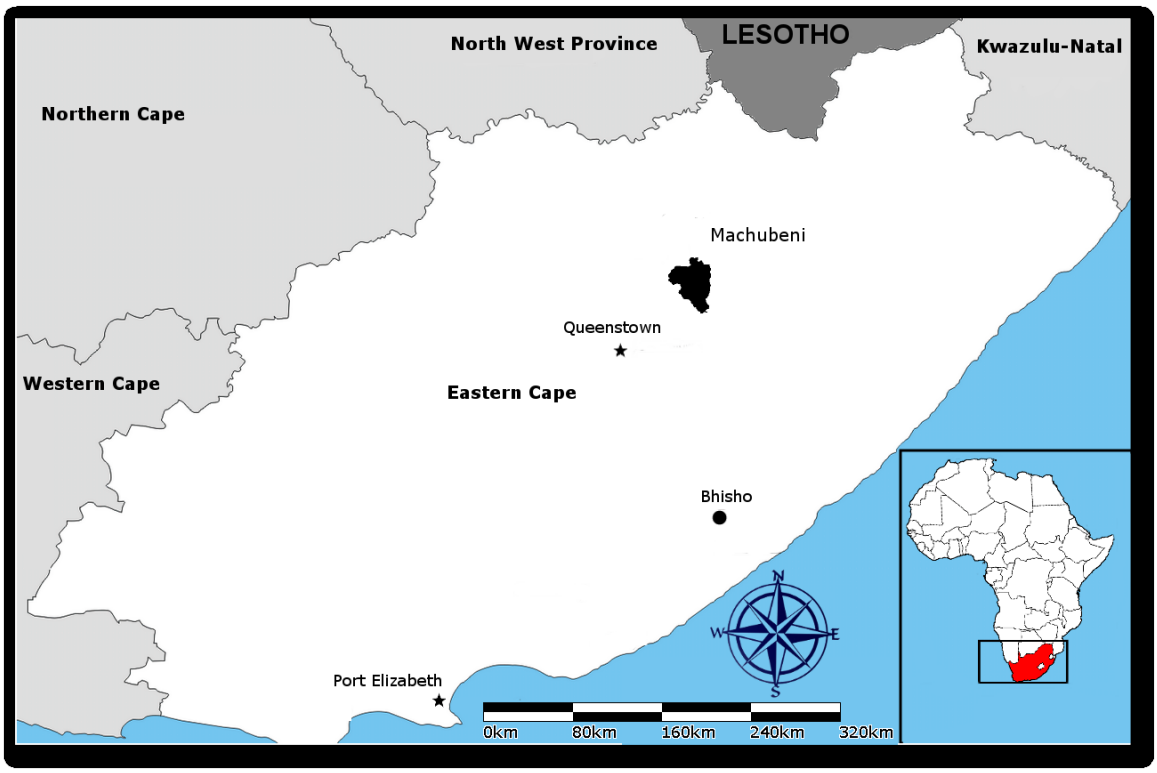

Figure 3-1: Location of Machubeni within the Eastern Cape, South Africa.

Livestock ownership is prevalent within the community, with over a third of households owning stock, primarily in the form of cattle and sheep. The average ownership across Machubeni is 10 large stock units (LSU) per stock owner. The grazing of livestock remains largely unregulated, with minimal fencing between villages, and few divided grazing camps.

These factors have resulted in Machubeni being described as one of the most ecologically degraded areas in South Africa, as well as being identified as one of the poorest communities in the country (Hoffman & Ashwell 2001, Cundill & Fabricius 2009).

Previous studies and projects in the area indicated that the community could benefit immensely from the implementation of biogas digesters due to its relative poverty and dependence upon declining natural resources (Shackleton & Gambiza 2008, Cundill & Fabricius 2009). Additionally, five bio-digesters were installed in Machubeni as part of a project by the Water Research Commission (Project K5/1955) to provide clean energy and promote sustainable land management through the use of waste slurry as an organic fertilizer for both food crops and fodder for livestock

3.2.2 Data collection through use of community survey

The study consisted of a household survey based on those used by Austin and Blignaut (2008) and Shackleton et. al (2007) to determine the current energy profile of households within the community (Appendix 1). Before administering the questionnaire ethical concerns were considered and permission obtained from local tribal authority, additional translation assistance was provided by a committee consisting of elected local community members. The initial survey was administered between March and April 2012 (Autumn) to 90 households within the Machubeni community across several of the villages within the area. One year later a follow-up survey was conducted to determine changes in perceptions regarding biogas technology and the usage of biogas as a primary energy source (Appendix 2). Interviews were administered in the preferred language of the respondent, which was mainly isiXhosa, and occasionally English.

Sampling was randomised through the use of a 20 sided polyhedron dice which was used on a municipal list of registered houses in the area. Data collection included weekends to avoid bias against working households. The questionnaires captured details through the use of both closed and open-ended questions, focusing primarily upon which energy sources were used for lighting, heating and cooking. The usage of each energy source, as well as household preference for each activity, were also recorded along with the frequency of use, quantity, and relevant collection details. Households with a fuelwood pile at the homestead

at the time of the interview were requested to set aside the typical amount of wood used daily. This fuelwood was subsequently weighed using a spring balance to the nearest 0.5 kg. Details regarding water access and consumption, as well as possible small-scale vegetable cultivation, were also recorded. Lastly, the perceptions of households regarding the use of biogas as a source of energy to satisfy their daily energy needs were queried specifically with regards to their desire to use biogas versus other energy sources for cooking.

3.3 Results

3.3.1 Household Energy Profile

We can see that five energy sources dominate the region, with a minor usage of gas noted (Figure 3-2). Despite many households engaging in subsistence farming, none of the respondents used crop residues.

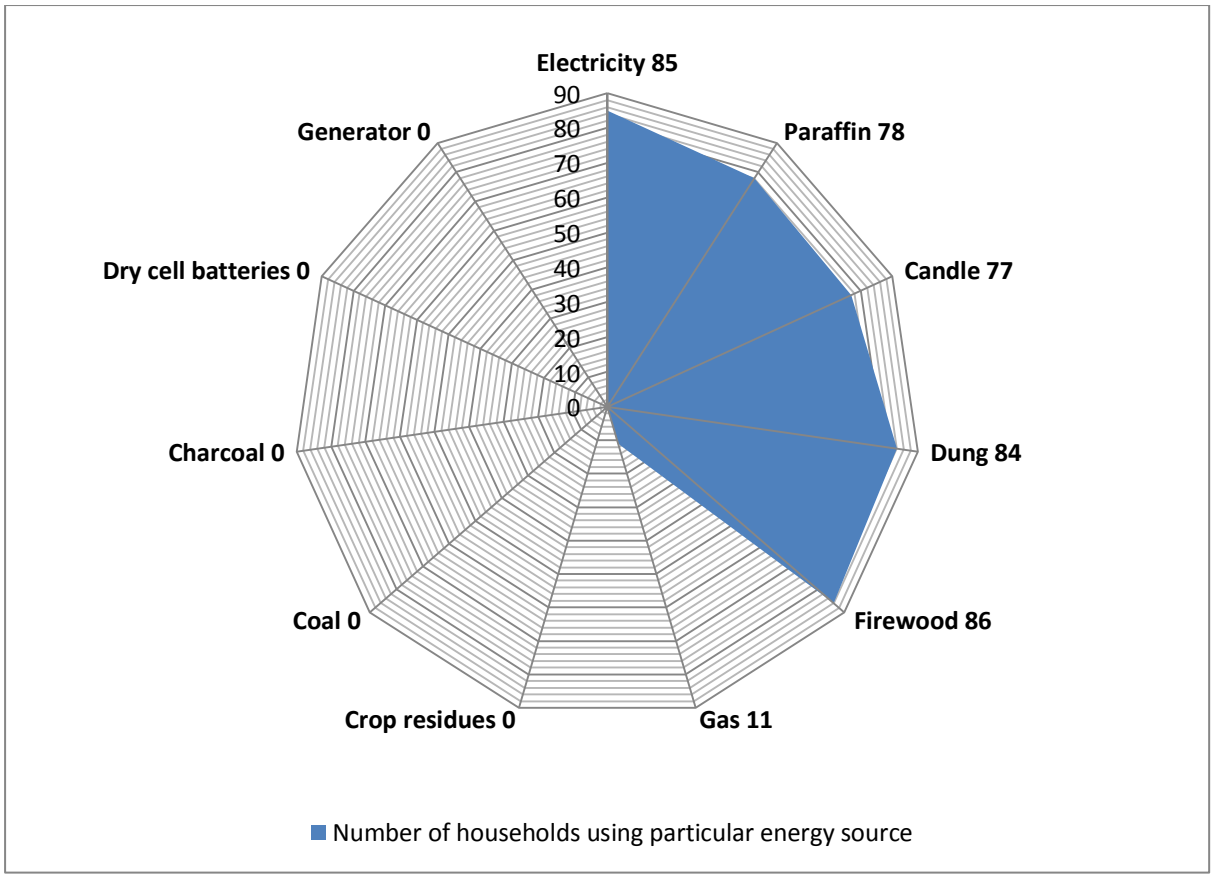

Figure 3-2: Energy source usage per household. The sample size was 90.

Household lighting is predominantly provided by a municipal electricity grid, paraffin and candles, whereas cooking is accomplished using a wider variety of energy sources (Figure 3-3). The use of fuelwood and livestock manure (referred to as dung henceforth) was widespread amongst households for the purposes of cooking and heating, though electricity usage for cooking was still observed (Figure 3-3). Whilst paraffin and gas were used by households, neither was considered to be the most important energy source for any of the three primary activities surveyed though many did cite its value for heating during winter months. All surveyed households used fuelwood and dung for the purposes of cooking (Figure 3-3). Dung was considered to be a supplementary fuel source along with paraffin (Figure 3-4).

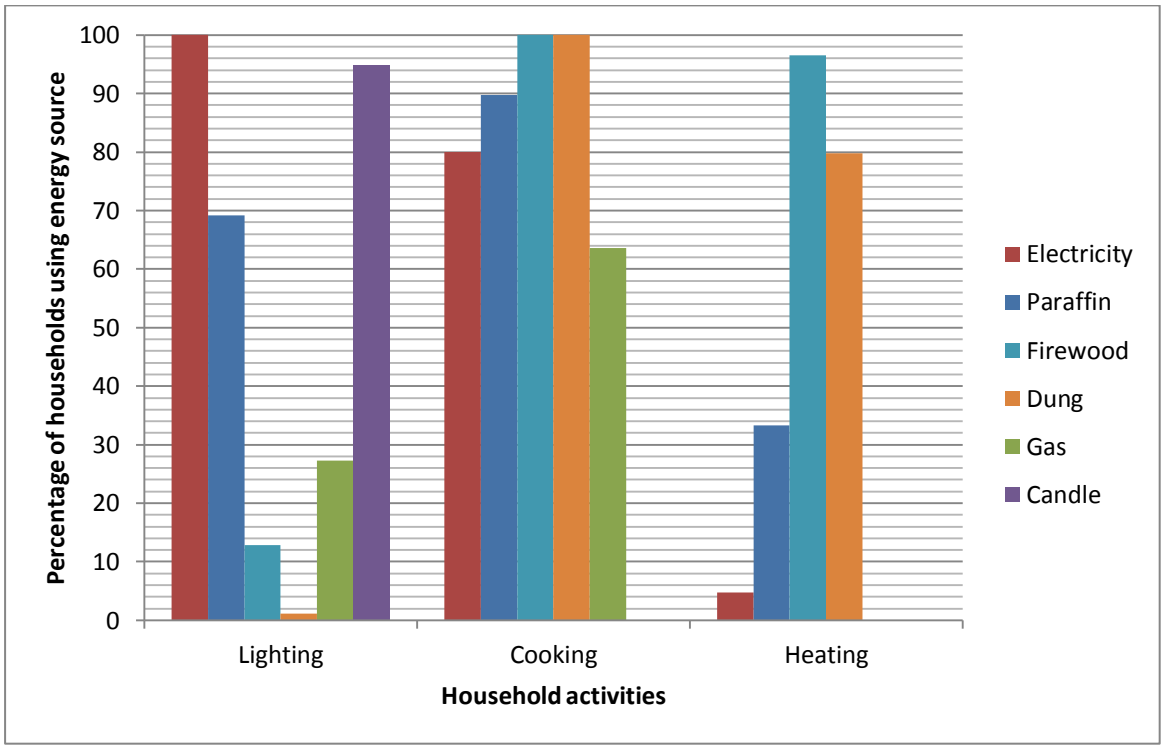

Figure 3-3: Percentage activity usage of energy sources. The sample size was 90.

The majority of surveyed households considered electricity to be their most important energy source for both lighting and cooking (Figure 3-4). Overall it was observed that fuelwood and electricity are two of the most important energy sources used by households to satisfy their daily needs.

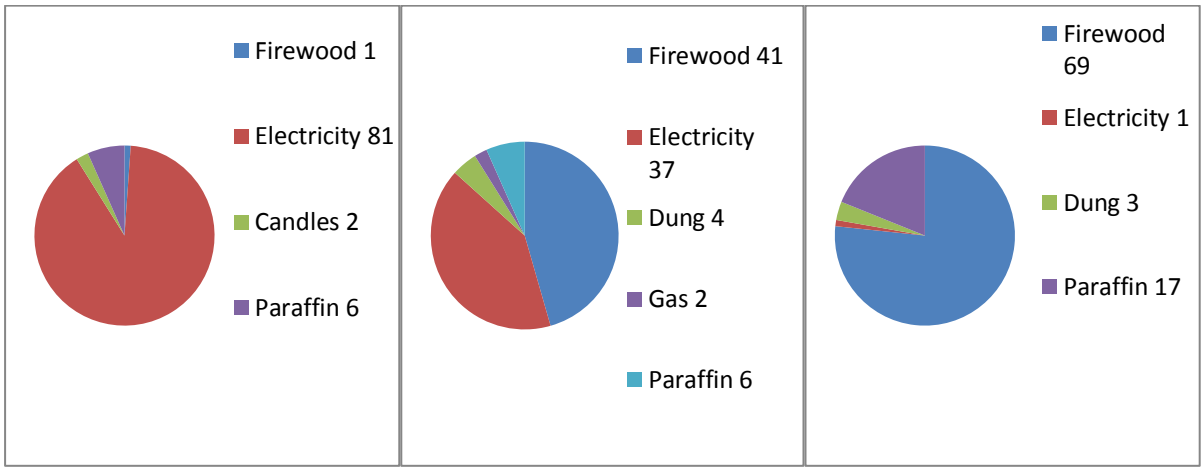

Figure 3-4: Number of households using different energy sources for lighting (left), cooking (middle) and indoor heating (right). The sample size was 90.

Despite the danger of accidental interior fires and health risks associated with smoke inhalation, many households indicated that they frequently made indoor fires (Figure 3-5). This was due to the cold outdoor conditions as well as the additional heating provided by indoor cooking. There was significantly more cooking taking place over winter months indoors.

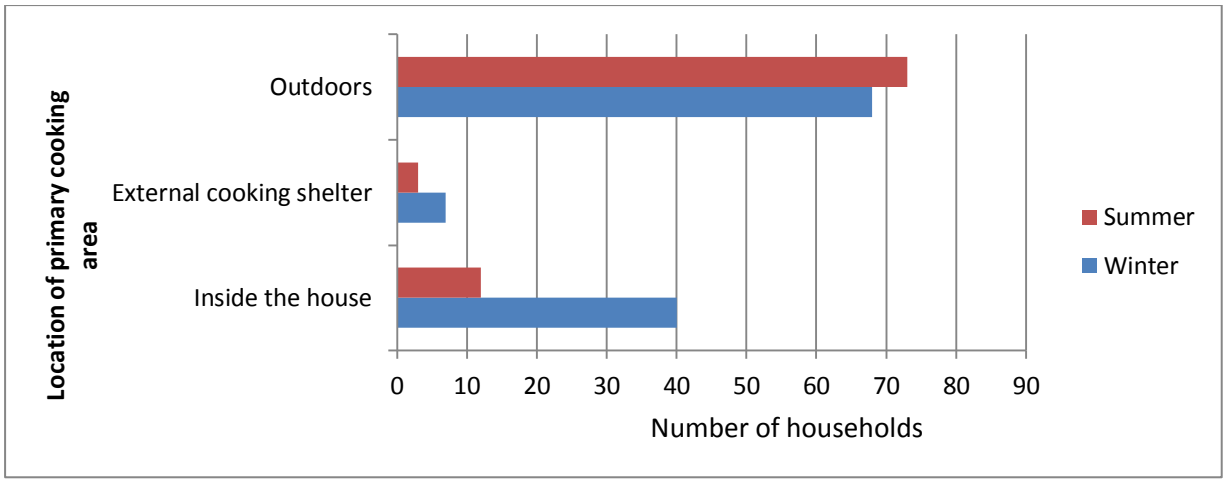

Figure 3-5: Areas where the fire is made. The sample size was 90.

The vast majority of fires were made within simple braziers, which when examined were simple zinc cylinders (often an old bucket) with holes punched in them (Figure 3-6).

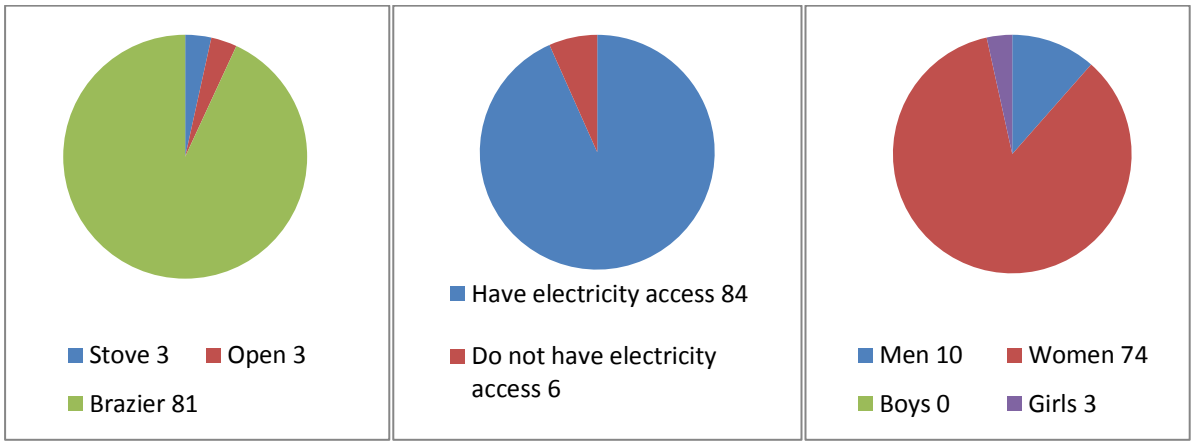

Figure 3-6: (Left) Number of households using different vessels in which to make fire. The sample size was 87.

Figure 3-7: (Middle) Number of households that have electricity access. The sample size was 90.

Figure 3-8: (Right) Number of individuals (by gender) who collected firewood. The sample size was 90.

Electricity was the most widely used energy source with 93.3% of households reporting access (Figure 3-7). Most fuelwood within the area was collected by adult women (Figure 3-8) with fuelwood usage of approximately 12.5 kgs per day (Figure 3-9). There are, however, significant variations regarding the daily fuelwood usage across households.

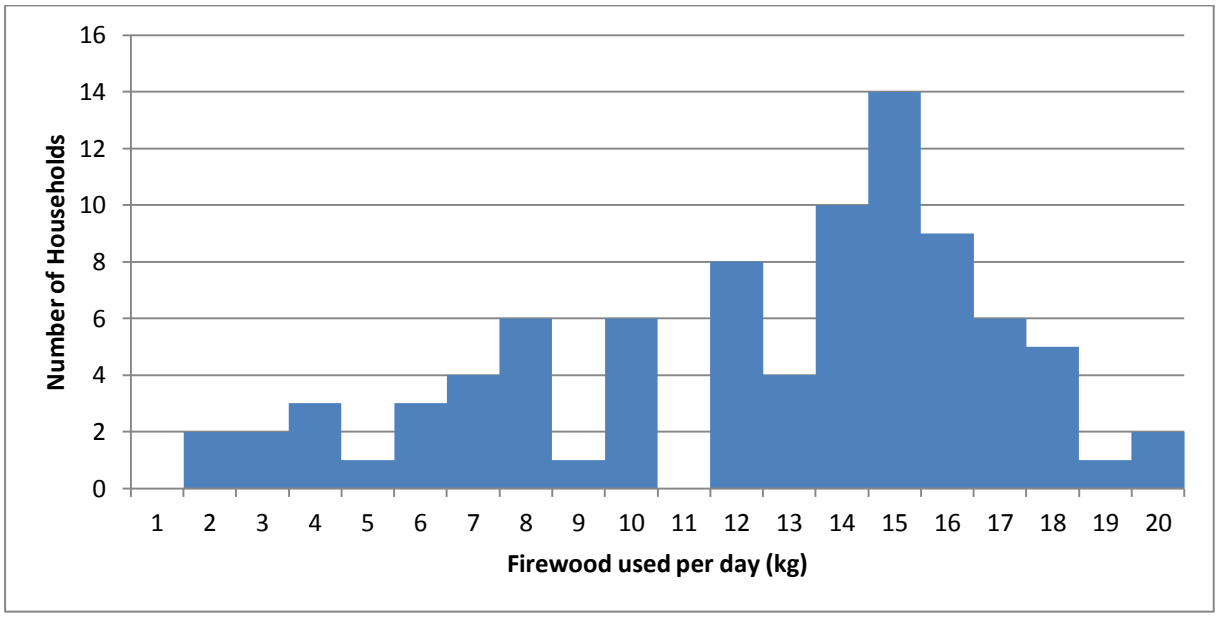

Figure 3-9: Daily household fuelwood consumption. The sample size was 90.

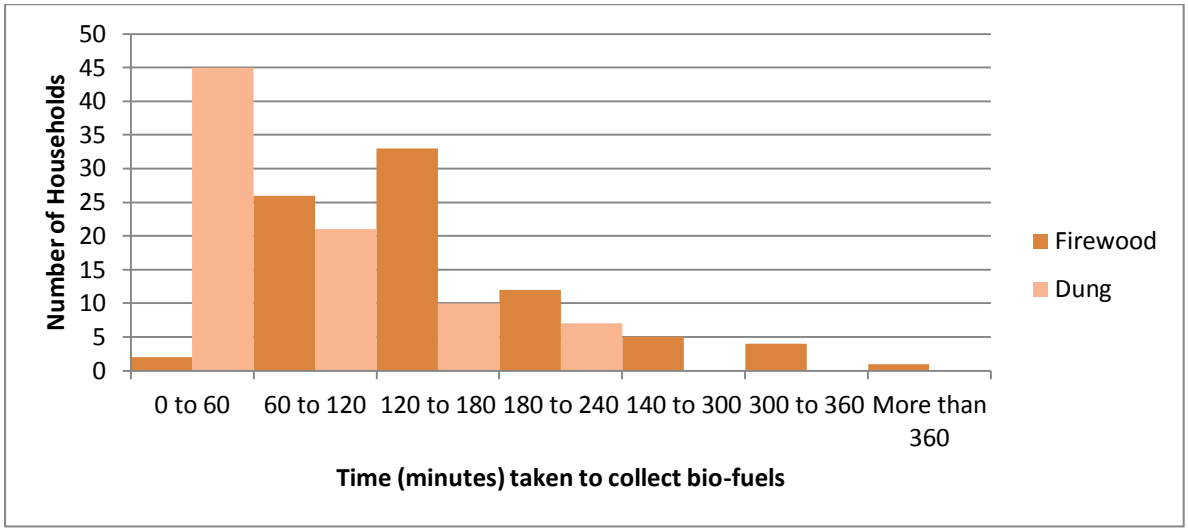

Figure 3-10: Time (minutes) to gather bio-fuels. The sample size was 90.

Table 3-1: Time (minutes) taken to gather bio-fuels. The sample size was 90.

Firewood		Dung	
Mean	182.8	Mean	94.1
Mode	180	Mode	60
Median	180	Median	60
Range	390	Range	480

Dung is mostly scavenged from either the households own kraal or from the communal fields nearby. Most households were able to collect sufficient dung for their needs at substantially lower distances in comparison to fuelwood (Figure 3-11)(Table 3-2).

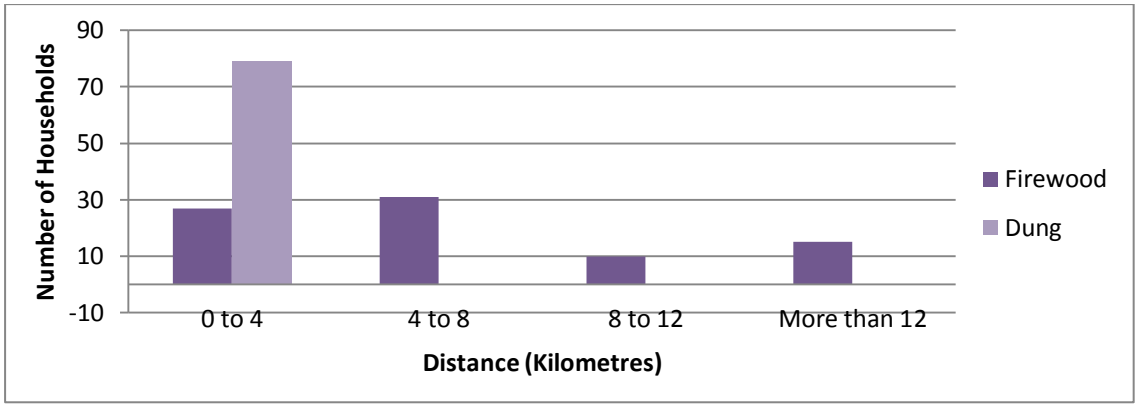

Figure 3-11: Distance travelled to collect bio-fuels. The sample size was 90.

Table 3-2: Distance travelled to collect bio-fuel (km) The sample size was 90.

Firewood		Dung	
Mean	7.3	Mean	2.5
Mode	3	Mode	3
Median	7	Median	2
Range	15	Range	10

Firewood is collected at almost the same mean frequency between summer and winter; this is despite the drastic temperature changes that occur in the region (Figure 3-12) (Bolus 2009). This is indicative of households stockpiling firewood throughout the year as evidenced by large wood stockpiles that were present at most households which collected firewood. If we combine the mean frequency of collection per week from Table 3.3 and Table 3.4 (fuelwood and dung respectively), we can estimate that 12.3 hours on average are spent every week just gathering the needed resources for that week.

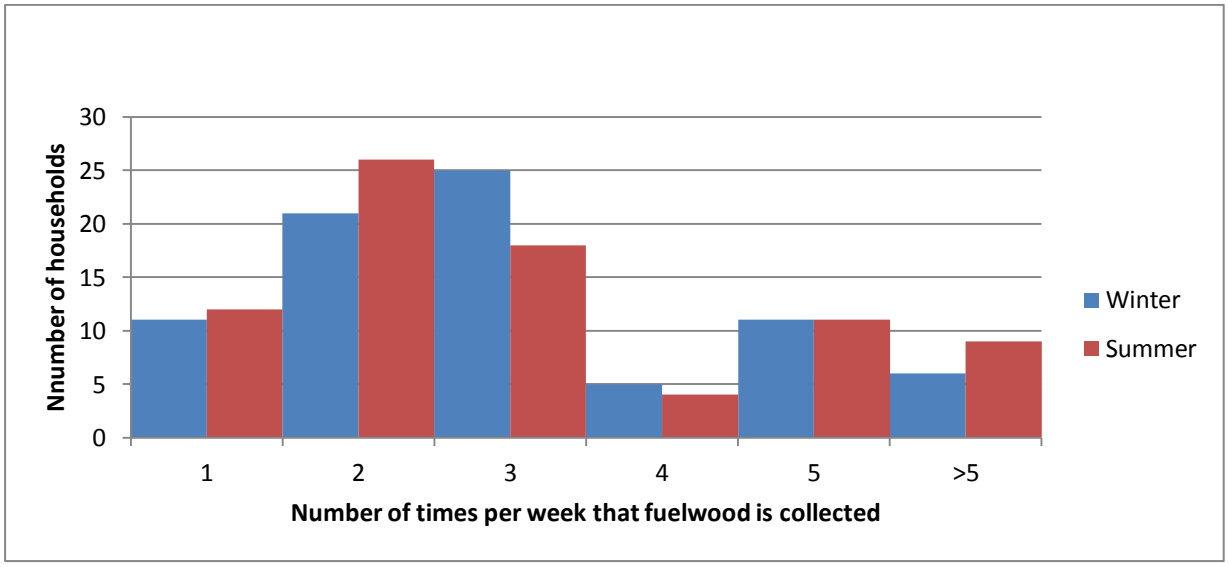

Figure 3-12: Weekly fuelwood collection. The sample size was 90.

Table 3-3: Frequency of collection of fuelwood per week (Kg). The sample size was 90.

	Winter	Summer
Mean	2.8	2.9
Mode	3	2
Median	3	3
Range	7	7

Dung also appears to be collected at almost the same mean frequency between summer and winter as fuelwood (Figure 3-13).

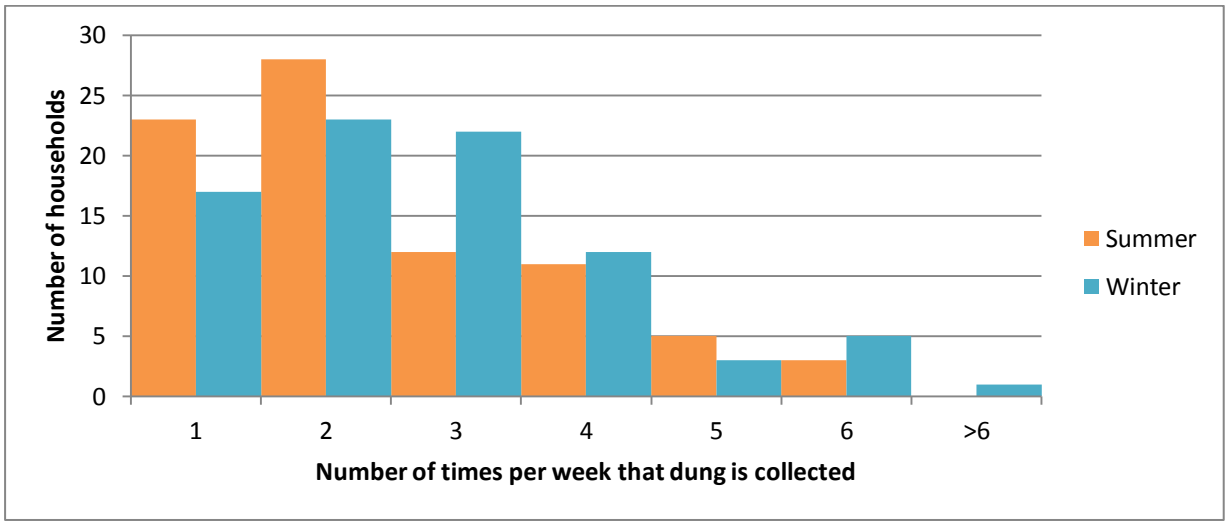

Figure 3-13: Frequency of collection of dung per week. The sample size was 90.

Table 3-4: Frequency of collection of dung per week (Kg). The sample size was 90.

	Summer	Winter
Mean	2.3	2.6
Mode	2	2
Median	2	2
Range	6	7

Electricity is clearly the preferred energy source with a 35% difference between its closest competitor (biogas). It should be noted that all the benefits of biogas were explained prior to this question; economic benefits, food security, sustainability and cooking benefits, and, therefore, this perception may be biased due to lack of experience with biogas (Chapter 4).

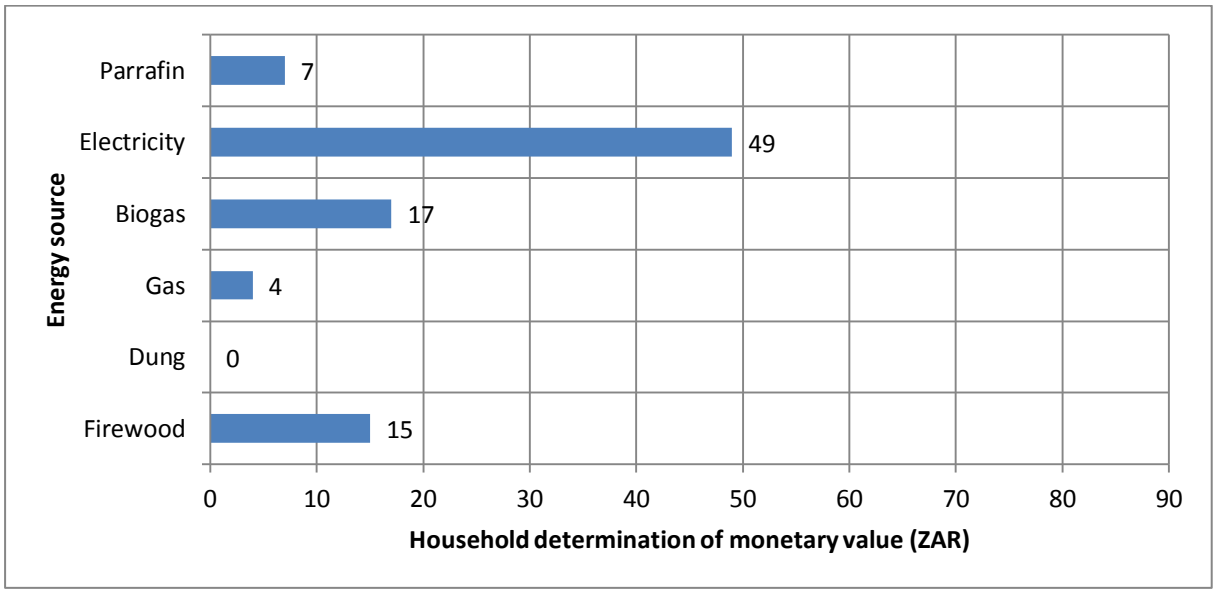

Figure 3-14: Preference for energy source assuming equal price (R). The sample size was 90.

Fuelwood collection took place on average three times a week (Figure 3-14) with the households gathering multiple days' worth of fuelwood in a single trip.The cultivation of small-scale vegetable gardens and crops (primarily maize) by households was observed, however, few were using any form of fertilizer and the preferred fertilizer of choice was livestock manure with no significant usage of commercial fertilizer (Figure 3-15).

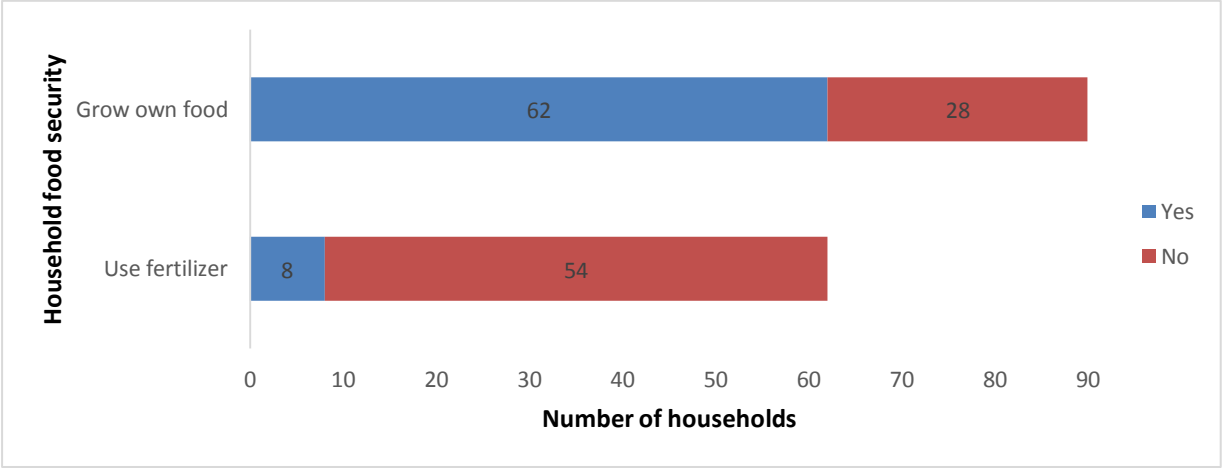

Figure 3-15: Households that grow their own food. The sample size was 90.

3.4 Discussion

3.4.1 Biomass as a predominant energy source

Throughout the Machubeni community, biomass usage in the form of dung and fuelwood have proven to be widespread especially for the activities of daily cooking and heating. This continued reliance on biomass is well-defined feature of underdeveloped rural communities and is especially prevalent in sub-Saharan Africa (Jumbe et al. 2009, Brew-Hammond 2010, Martinot 2013) this is in spite of the drastic increase in electricity access, whereby over the past decade the majority of households have been connected to the national grid. This is reflective of literature indicating that households take the time to change their energy profiles, even when newer more efficient energy sources become available, a phenomenon that has been observed within rural South African communities before (Madubansi & Shackleton 2006).

3.4.2 Household resilience in the form of multiple energy sources

Households in the Machubeni community maintained multiple energy sources even after being connected to the national electrical grid, which was overwhelmingly a favoured energy source. Both candles and paraffin were often used in instances where electricity was unavailable, which happened to frequently during periodic thunderstorms and heavy flood events.

Biomass was also often cited as a backup for both cooking and heating, though this was less prevalent in the case of heating, with few electric heaters or blankets being used by households. Household usage of dung was primarily supplementary, and it was not considered to be the most important or primary energy source.

Tendencies towards the usage of electricity, due to its versatility were exhibited by surveyed households, though the reported amount of electricity used was variable. The large spikes exhibited in Figure 3-14 could possibly be due to the different levels of technology present in each household. Households who primarily used electricity only for lighting tended to fall within the R20 to R60 region. Whereas households who use electricity for cooking and heating in addition to lighting paid higher amounts.

3.4.3 Health ramifications of indoor dung and wood fuel use

The particulate emissions associated with the indoor burning of dung and fuelwood is problematic due to the direct links between air quality and human health (Gautam et al. 2009, Bond & Templeton 2011, Gwavuya et al. 2012, Huong et al. 2014, Smith et al. 2015). The manner in which community is so heavily reliant upon this inefficient and dangerous energy source is an indication of the dire socio-economic status of them. Fuelwood and dung both have substantially lower thermal efficiencies than biogas with 17% and 11% respectively, whereas biogas is noted at being as high as 75% (Smith et al. 2015).

Households were observed to lack adequate ventilation, thus increasing susceptibility to breathing related illnesses due to emissions from smoke inhalation. This was exasperated by the use of inefficient braziers versus the use of improved cookstoves, which burn more efficiently and can improve indoor air quality through the use of chimneys (Martinot 2013). Without adequate ventilation, the burning of wood indoors can lead to a build-up in particulate emissions of <2.5 μm, which are noted to have the greatest impact on respiratory health (Bruce et al. 2011, Gwavuya et al. 2012, Smith et al. 2015). Particulate and carbon monoxide emission from biogas is much lower in comparison than both dung and fuelwood, and its usage can potentially lower health risk from both respiratory and cardiovascular diseases by 20 – 25% (Semple et al. 2014).

The burning of dung also serves to interrupt the natural nutrient cycle whereby dung naturally decomposes enriching soil and assisting in ensuring food security. This reduction in fertility has far reaching and long term implications when considering fertility and availability of arable land (ISAT/GTZ 1999a, Feng et al. 2009, Massé et al. 2011, Austin & Morris 2012, Gwavuya et al. 2012). This reduction in nutrient cycling is also evident from the minimal usage of manure for the purposes of fertilizer by households within the community, with most opting to rather burn the dung for warmth.

3.4.4 Household reliance on fuelwood

E. floribundas is the predominant source of wood in the community, with almost 97% of the fuelwood supply consisting of it (Shackleton & Gambiza 2008). It is an invasive species of small multi-stemmed shrub that is sometimes used by the local populace for medicinal purposes, but primarily as a fuelwood. Whether this is because it is a favoured species, or because it is one of the few remaining useful species in degraded environments such that inhabitants have little another choice, is unknown. It is an inferior source of fuelwood to other woods in neighbouring provinces, and its gathering is slow and laborious, with the collection of juvenile shrubs involving removing the entire shrub instead of clipping stems or collecting fallen branches. Replacing this low-grade fuelwood with biogas would mean a higher energy efficiency as well as a reduced gather time for the locals with gather times for fuelwood already reaching three hours on average (Table 3.2).

Households also appear to spend a significant amount of time collecting their fuelwood, covering large distances with weighty bulky loads to accumulate significant wood piles. These lengthy time periods may increase in the future due to the clustered distribution of *E. Floribundus* within the study area. *E. Floribundus* tends to grow in largely isolated patches instead of being evenly distributed and, therefore, the distance to gather fuelwood may vary, however due to the destructive nature of harvesting this woody shrub. This usually entails the complete removal of the shrub, versus the collection of dead wood and necessitates households travelling further as time progresses. This particular area of study requires more focus as these observations were not central to this study.

The gender dynamics regarding fuelwood collection indicated that 85.6% of all fuelwood collection was performed by adult females, who were also responsible for preparing most meals. By reducing the time spent on these tasks biogas technology has the potential to significantly improve the lives of Machubeni households by creating additional time for these women and reducing the physical hardship of fuelwood collection. By using readily available feedstock in the form of livestock manure, crop residues and leftover vegetable waste, bio-digesters could potentially provide an additional form of energy to add to the household's energy profile whilst also improving their health and food security.

3.5 Conclusion

Households within the Machubeni community exhibited an array of energy sources with a heavy reliance on bio-fuels, especially with regards to fuelwood and livestock manure. Despite access to electricity these rural households have retained resilience with regards to their energy usage and have a variety of backup energy sources for the intermittent power failures experienced by the area. They also retain large wood stockpiles throughout both summer and winter to ensure that they have supplementary energy reserves. Overall the community is an ideal candidate for the implementation of biogas technology in the form of bio-digesters due to the suite of benefits which could be provided by the technology.

CHAPTER 4 : PERCEPTIONS AND EXPERIENCES OF BIOGAS PRODUCTION AT RURAL HOUSEHOLD SCALE IN SOUTH AFRICA: MACHUBENI A CASE STUDY

4.1 Introduction

Worldwide, roughly 1.3 billion people continue to lack access to electricity and 2.6 billion rely on biomass fuels including wood, dung, agricultural residues and coal to supply their energy needs (Martinot 2013). These households are heavily dependent upon biomass as their primary energy source and whilst these low-cost biomass energy sources have managed to sustain the livelihoods of communities in the past, the tipping point with regard to environmental degradation is quickly becoming apparent (Scheffer 2010). In Chapter 2 the ever pressing need for sustainable development was discussed alongside the merits of bio-digesters.

One of the major barriers towards implementing biogas in Africa is the difficulty in changing the perceptions of the households regarding the adoption of a new energy system (Akinbami et al. 2001, Sibisi & Green 2005). Even when more efficient and user-friendly energy sources are available, the dynamics and factors surrounding adoption are not simple and, therefore, the initial and changing perceptions of communities with regards to any new energy source are an important component in determining the success of implementation and adoption. By incorporating and consulting with the communities from the onset of implementation it is possible to identify potential pitfalls and facilitate social learning.

Unfortunately, no accepted universal theorem for social learning exists (Wals 2007). Sources differ on the importance of individuals learning whilst in social settings while others refer to the group or society as a whole rather than singling out individuals (Parson & Clark 1995). Wildermeersch et al. (2007) defines social learning as learning that takes place in groups or social systems that operate in new, unexpected, uncertain and unpredictable circumstances whereas Bandura & Albert (1963) describe social learning as taking place between individuals through their interaction and observation of others in a group.

Throughout this chapter, social learning is defined as a collective action and reflection that takes place amongst both individuals and groups when they work to improve the management of their energy systems (Keen et al. 2005). Overall this paper aims to investigate the changes in perceptions and user experiences within the study site community highlighting the importance of social learning towards the success of subsequent bio-digester projects within rural households.

4.2 Materials and Methods

4.2.1 Study site

The study was conducted in the Machubeni community. A description of the study site is provided in Chapter 3.

4.2.2 Data collection in the form of community surveys

Community surveys were administered using standardised survey methods. Further details of the data collection are detailed in Chapter 3.

4.3 Results

4.3.1 Household's knowledge and perceptions of biogas technology

Initial surveys reported minimal knowledge of biogas technology or bio-digesters within the Machubeni community, with only seven percent of households responding indicating prior knowledge of biogas. Despite basic awareness of biogas, none of the initial respondents were able to provide substantial details regarding the biogas technology and it was compared to the more predominant LPG gas being used in the area.

Surveys after the bio-digesters had been installed and operational for approximately one year indicated a significant increase in awareness of biogas as an energy source with 82% of households reporting awareness and basic knowledge of the operation and potential benefits of bio-digesters. Despite only five bio-digesters being installed across three of the villages within the area, households were found to be well informed, with numerous households indicating having visited the bio-digesters themselves.

4.3.2 Household acknowledged benefits of biogas

About 50% of households stated that the most important benefit of biogas was for cooking (Figure 4-1). Economic benefits were the least acknowledged benefit according to households with only 13% of households indicating awareness of this benefit (Figure 4-1). Sustainability and contribution to food security benefits were acknowledged at 18% and 21% respectively (Figure 4-1).

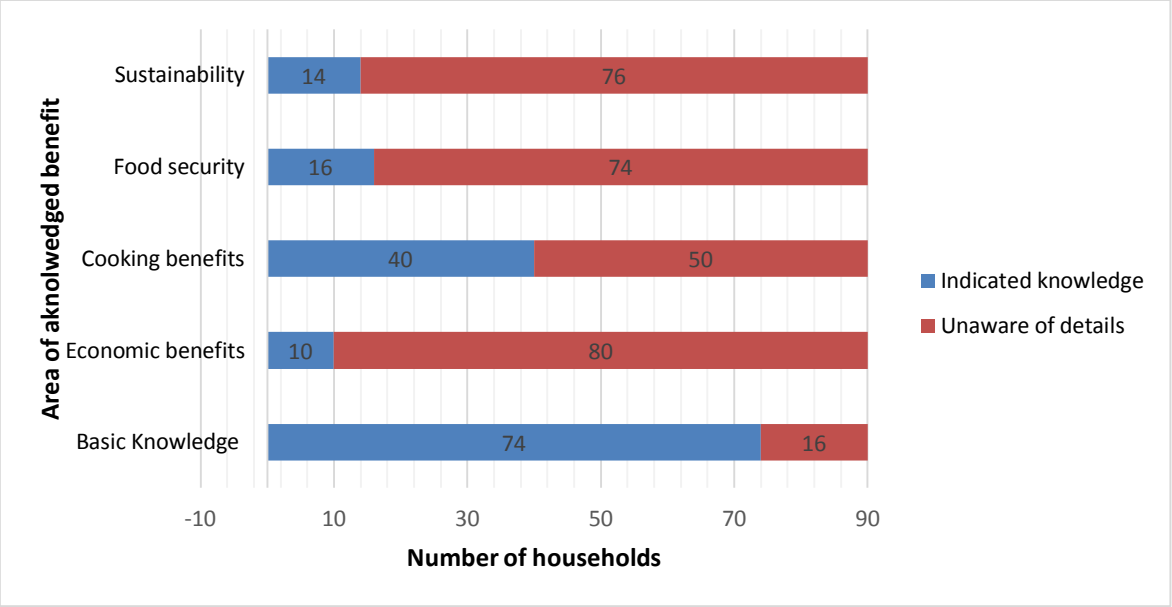

Figure 4-1: Household knowledge and perceptions regarding biogas post implementation. The sample size was 90.

Gender dynamics are heavily skewed within the community, with food preparation being performed primarily by the women in the households, with a similar trend regarding the duties of collecting fuelwood. Households displayed no aversion towards the usage of biogas for cooking purposes (Figure 4-2) and in fact expressed enthusiasm towards the prospect of using a fast burning instant energy source that could be produced through the use of a locally available resource.

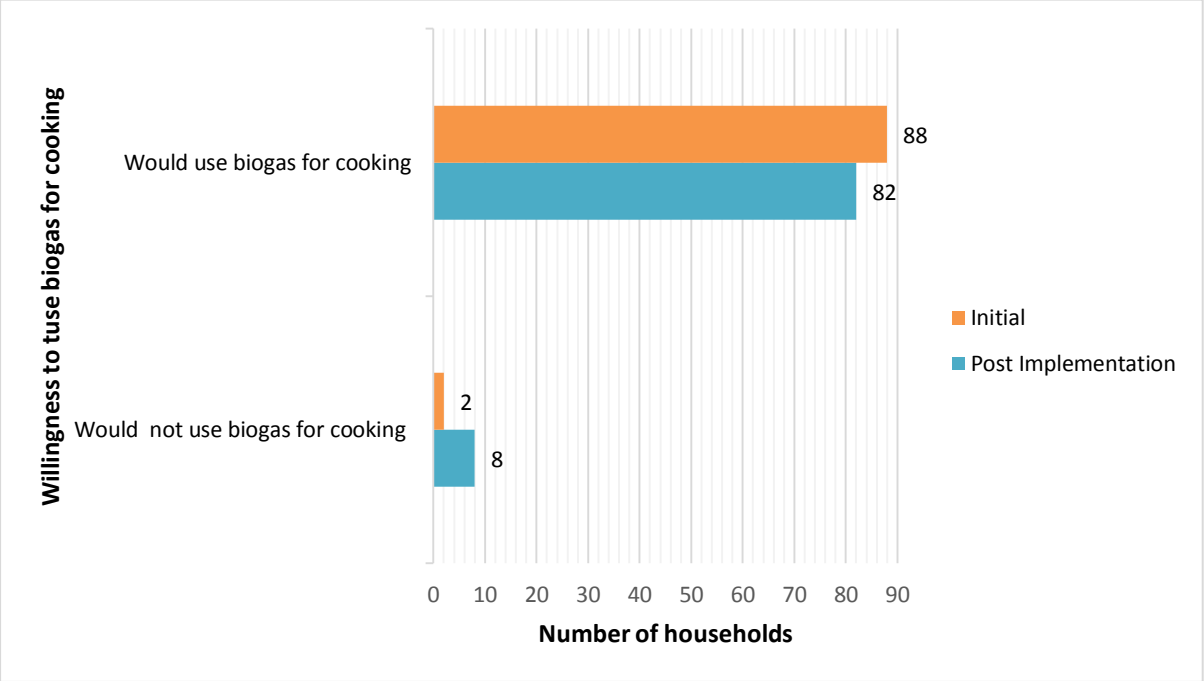

Figure 4-2: Household desire for biogas. The sample size was 90.

Household perceptions regarding their valuation of services delivered by biogas fluctuated minimally between the initial survey and after implementation, with a tendency for households to be willing to pay approximately R50 per month (Figure 4-3).

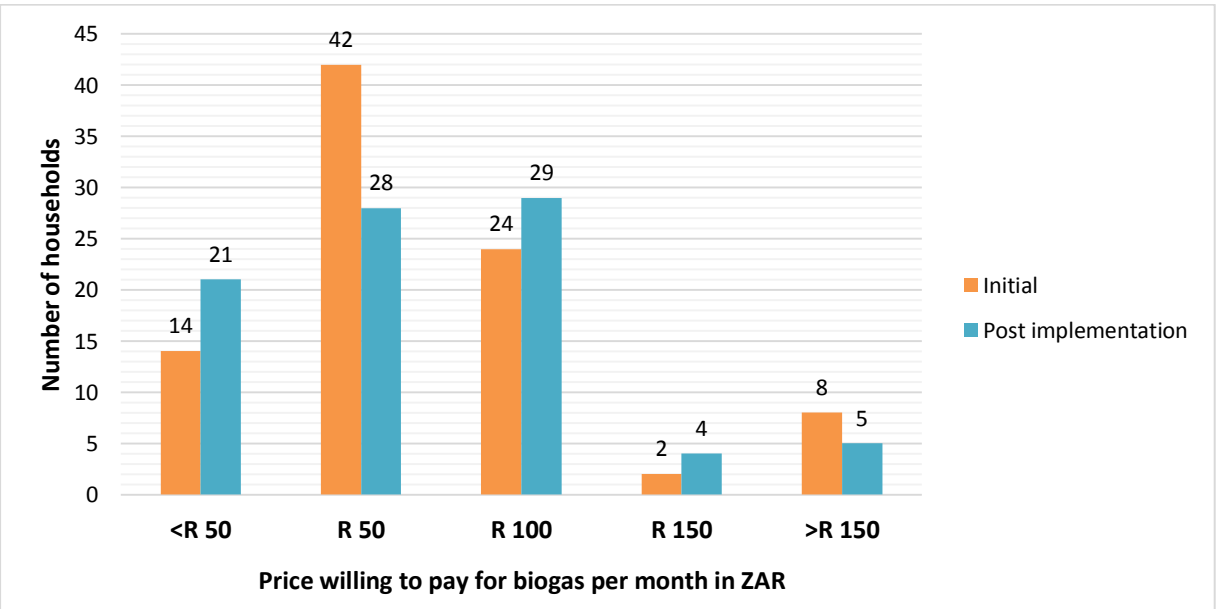

Figure 4-3: Willingness to pay for biogas. The sample size was 90.

The expressed desire of households towards bio-digesters was significantly positive, with the majority of households expressing a desire to install upon their property (Figure 4-4). Additionally 85% of households in the initial survey expressed confidence in their ability to collect sufficient feedstock and water for daily bio-digester operation (20kg & 20 L). However, there was a decrease in the number of households willing to commit to this task after the installation of the pilot bio-digesters in the area. Possible reasons regarding this decline include the limited functionality of the pilot bio-digesters during the study period combined with the realities of the need for the continual feeding of bio-digesters by households.

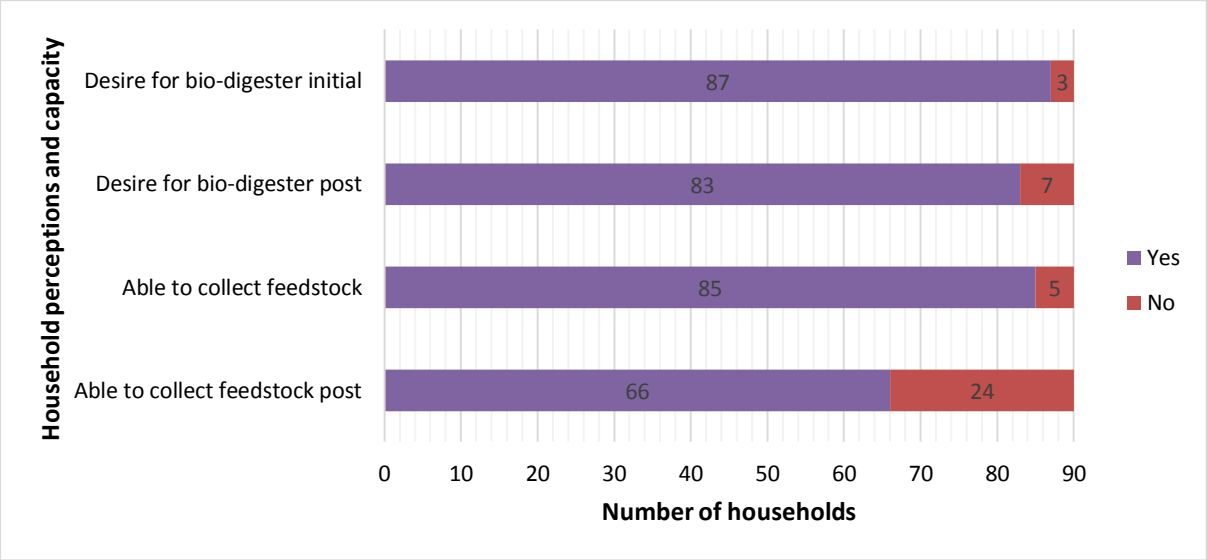

Figure 4-4 Household desire and capacity to operate bio-digesters. The sample size was 90.

Only 68.9% of the sample practiced subsistence farming, with the only reported fertilizer being cattle dung (Figure 4-5). The households expressed their belief that the dung would be better used as an energy source or as a building material, rather than as fertilizer.

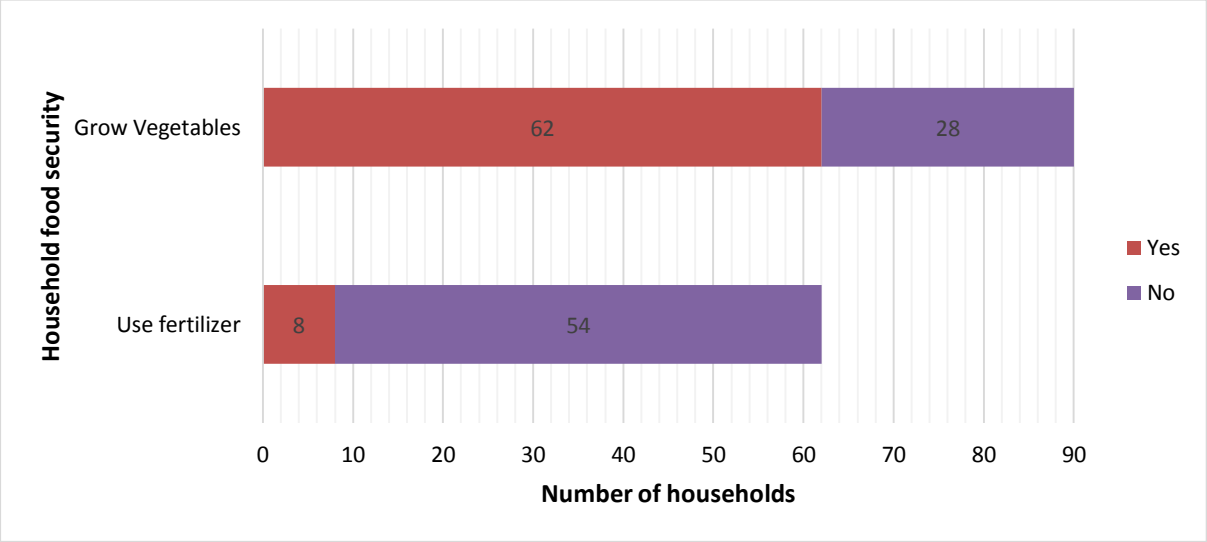

Figure 4-5 Household food security. The sample size was 90.

4.4 Discussion

4.4.1 Increases in awareness and specific biogas knowledge

The facilitation of knowledge transference this process was achieved through the organisation of informational sharing workshops. Several of these were hosted by the households which had bio-digesters installed whilst others took place within a community hall central to the villages in the area. Workshops were mediated by biogas experts who provided accurate and concise information regarding the technical operation of the systems whilst providing answers to encouraging questions. This increase in knowledge was limited to basic awareness, with specific knowledge regarding the benefits of biogas technology remaining low with most benefits being acknowledged by less than 20% of households. The exception to this was the usage of biogas as a primary energy source for daily food preparation, which was one of the most commonly acknowledged benefits by many other projects around the world (Akinbami et al. 2001, Walekhwa et al. 2009, Tu et al. 2011, Bruun et al. 2014, Surendra et al. 2014). It was this dissemination of detailed knowledge throughout the entire community over the research period that substantiated the claim of social learning taking place. Initial knowledge of biogas technology and its many benefits was limited at the onset of this project, however after a single year of operation, there was a significant increase in awareness within the community over a one year period.

Economic benefits were unremarked upon, despite the high incidences of unemployment in the area and scarcity of local fuelwood, with households spending significant portions of their day collecting both livestock manure and fuelwood. This can be partially accounted for due to the limited number of bio-digesters installed in the study areas, as well as the technical issues experienced by these households resulting in a total biogas yield which was intermittent and below optimal (Chapter 5). Despite the prevalence of small-scale vegetable gardens within Machubeni, relatively few households remarked upon the ability for bio-digesters to assist in food security through the production of nutrient-rich slurry.

4.4.2 Importance of wood fuel as an energy source

One challenge commonly linked to the adoption of biogas as a primary energy source for cooking is the cultural perception that meals cooked using fuelwood are more 'flavourful' and, therefore, preferable (Akinbami et al. 2001). Households in Machubeni, however, exhibited no significant bias towards or against the use of biogas for the purposes of meal preparation. One explanation for this is the limited access to quality fuelwood in the area with *E. floribundus* being the only readily available fuelwood in the area. This small multi-stemmed shrub is widely distributed in South Africa, however, it is commonly found in the Eastern Cape Province. It can reach heights of 2.5 meters in protected environments, however, is usually less than 75 cm (Shackleton & Gambiza 2008). This woody shrub is heavily utilised by the community and due to lack of alternatives is often the sole species of fuelwood harvested (Chapter 3; (Shackleton & Gambiza 2008). This is despite difficulty with regards to harvesting this species as well as its limited calorific value as a fuelwood. Households spend an average of nine hours a week collecting firewood from extensive distances (Chapter 3) and this task falls primarily on the shoulders of women who are also responsible for the daily preparation of meals in the community. By reducing the reliance upon fuelwood, lengthy collection times can be reduced as well as reducing total food preparation time due to the convenience of biogas appliances versus tending a fire. The reduced emission of particulate matter in the form of smoke was reported upon by households, which is also a well-documented advantage of biogas (Gautam et al. 2009, Bond & Templeton 2011, Gwavuya et al. 2012, Huong et al. 2014, Smith et al. 2015).

4.4.3 Changes in perceptions

The difference between perceptions before and after installation of the bio-digesters in the community are minor, with the overwhelming majority still considering biogas a desirable energy source. What is interesting to note is the reduction in confidence with regards to capacity to operate the bio-digester, which decreased after the installation of the pilot bio-digesters. Reasons cited by households tended to be orientated around the inability to source appropriate feedstock, primarily fresh livestock manure and claimed that age and insufficient livestock were their prime concerns. The age factor was significant as the advanced age of many household members caused concern over their ability to collect feedstock for the bio-digesters every day. The concerns regarding livestock stemmed from the common practice whereby cattle are occasionally rotated to more distant pastures collectively, especially during drier winters, thus creating a localised shortage of fresh manure near many households. Ideal operation of bio-digesters requires the constant daily feeding of feedstock, with sufficient water to ensure hydrolysis (ISAT/GTZ 1999a, Austin & Blignaut 2008, Walekhwa et al. 2009).

4.4.4 Water access

Access to water was not considered an issue with most households using the freely available municipal water at accessible communal stand taps. This water supply is, however, intermittent at times and many households have resorted to using supplementary water sources such as the local river, rainwater tanks and in the event of long-term shortages municipal water tankers. Households felt confident that they would be able to collect at least 20 l of water daily for the purposes of running a bio-digester more so than their ability to provide adequate feedstock.

4.4.5 Household willingness to pay

This desire to install bio-digesters was however not matched by households willingness to pay for the expensive installation of the technology. A study of a similar community using the same model of bio-digesters in a similar rural region in Kwazulu-Natal found that in order to account for all financial costs households were required to pay a minimal amount of ZAR 390 per month over a period of 15 years (180 months) to install a single bio-digester(Smith et al. 2014).

Assuming the adoption of a government subsidy of ZAR 20 000, this amount can be reduced to ZAR 187 which is still well above the amount reported by households as their ideal valuation of bio-digesters. This is of course heavily influenced by the extreme poverty within the community, where governmental grants and benefits form a large proportion of the total household income. This financial barrier represents a significant challenge for the rapid and large-scale implementation of this technology, despite the long-term economic benefits afforded by the bio-digesters and its potential to assist in the achievement of numerous sustainable development goals, specifically energy access, gender equality, health benefits and food security.

These perceptions were primarily based on the experiences of the five households which had the bio-digesters installed at their homestead. These benefits were directly observed through the monitoring process and were remarked upon universally by all the operating households. Each of these households reported that they noted a marked difference in their lifestyles due to the bio-digesters and even in cases where technical difficulties resulted in below optimal biogas production. All households reported reduced fuelwood consumption and noted the ease of usage of biogas, with households incorporating the use of biogas into their daily routines, particularly for the rapid heating of water. Aside from these tangible benefits, the bio-digesters generated an immensely positive response from the community and have sparked major interest in the installation of renewable energy projects in the region.

4.5 Conclusions

In conclusion, the findings of my research strongly indicate the process of social learning taking place within the Machubeni community, whereby through interaction and self-reflection biogas awareness was rapidly disseminated. This was due to there being no knowledge whatsoever of biogas technology within the community at the onset of this study. Over a period of one year, the potential benefits of a bio-digester were well established throughout households within the community despite the limited number of bio-digesters actually installed.

The positive perceptions regarding the acceptability of biogas technology within the community were encouraging and further research into the replication of these findings within other rural households within South Africa would be beneficial for the rapid implementation of bio-digesters on a large scale. Overall observations with regards to the perceptions of the community indicate that households are keen to diversify their energy sources and desire biogas as a sustainable alternative to fuelwood.

CHAPTER 5 : CHALLENGES AND CONSTRAINTS FOR BIOGAS TECHNOLOGIES IN SOUTH AFRICA: A CASE STUDY OF MACHUBENI, EASTERN CAPE PROVINCE

5.1. Introduction

Equitable and affordable access to energy are one of the fundamental pillars of sustainable development. With a burgeoning human population, set to rise to 9 billion by 2050, the widespread implementation of renewable energy is this century's greatest challenge with regards to achieving sustainable development, and the widespread, rapid implementation of renewable energy sources (Eisenberg & Nocera 2005, Modi et al. 2005, Godfray et al. 2010, Martinot 2013). Addressing energy poverty utilising renewable energy is critical if the millennium developmental goals of poverty reduction and sustainable growth are to be achieved (Brew-Hammond 2010, Pegels 2010, ESCAP 2011, Griggs et al. 2013, Mandelli et al. 2014). Significant progress still needs to take place within the renewable energy sector, especially within developing countries, to secure energy access for the millions of households that live in energy poverty (Griggs et al. 2013). Anaerobic bio-digesters have been identified as an effective and reliable technology able to assist in providing energy to remote rural households that remain largely dependent upon biomass to fulfil their energy demands (Rao et al. 2010, Bond & Templeton 2011).

Biogas can be produced through the anaerobic fermentation of organic biomass (feedstock) within a sealed environment, often referred to as a bioreactor or bio-digester. The bio-digester provides a hospitable environment for methane-producing microbes, which break down feedstock over time, producing biogas as a by-product. The biogas produced typically consists of between 40% to 70% methane, with the remainder being primarily carbon dioxide, with traces of hydrogen sulphide and other gases (Sibisi & Green 2005, Arthur et al. 2011, Abbasi et al. 2012). The exact composition of the gas varies primarily due to feedstock used, ambient temperature, retention time and the technological design of the bio-digester itself (Kundu et al. 2014).

The potential benefits of this technology have been well documented, especially in developing countries such as China, India and Nepal, where bio-digesters have been installed on a massive scale in an effort to assist in poverty alleviation and rapid rural development (Gautam et al. 2009, Chen et al. 2010, Rao et al. 2010, Gwavuya et al. 2012, Poeschl et al. 2012a). One of the key advantages of bio-digesters is that feedstock material is readily available in rural areas with livestock manure, kitchen scraps or even crop residues, which are all easily digested. Due to the modular nature of biogas digesters, they are uniquely suited towards assisting development within African countries, especially within more remote areas (Amigun & Blottnitz 2007, Renwick et al. 2007, Hiemstra-van der Horst & Hovorka 2009, Amigun et al. 2011, Nahman et al. 2012). Scaling up production can be accomplished through the addition of bio-digesters in a parallel configuration, allowing for implementation at both household and village-scale with minimal design changes. Within the context of South Africa, several studies have been conducted to determine the potential of this technology at various scales, with consensus regarding the numerous benefits made possible (Karekezi 2002, Austin & Blignaut 2008, Amigun & von Blottnitz 2010, Murphy et al. 2011, Smith et al. 2014). However, despite its suitability, there has been a serious lapse in the implementation of biogas technology, especially within African countries, with few large-scale projects being initiated. The few exceptions include national projects that are currently underway in Kenya; Burkina Faso, Ethiopia, Uganda and Tanzania. These countries have established international partnerships with NGO's such as Hivos and SNV to implement biogas at a household level through 'The Africa Biogas Partnership Programme' (ABPP) (Ghimire 2013).

A number of technological challenges stand in the way of widespread adoption and use of bioreactors in the rural sector. Ensuring that the bio-digesters are capable of delivering sufficient flammable gas for daily cooking is the critical factor in determining the household's adoption of the technology and ensuring that they do not simply revert to their previous fuel sources (Barry et al. 2011, Brew-Hammond 2010, Bruce et al. 2011). Bio-digesters must thus produce sufficient gas for household needs, as well as be robust and hardy enough, that rural families do not require extensive training to maintain the bio-digesters themselves.

Despite the simplicity of the technology and its minimal moving parts, quality control of installation is one of the most challenging aspects of any large-scale biogas project (Brew-Hammond 2010, Black et al. 2011, Bruce et al. 2011). One of the most common faults reported by biogas users is low pressures or reduced gas production. This is most often caused by a leak in either the gas chamber of the bio-digester or the pipes supplying the stove (Cheng et al. 2014).In addition, adequate user training and constant maintenance are critical factors when ensuring the sustainability and longevity of bio-digesters. Despite the simplicity and robust design of bio-digesters, leaks and malfunctions can arise between the outlet valve and the gas appliance. The technological capacity to repair or replace these gas lines and fittings are often sorely lacking at many installations (Amigun et al. 2011, Okello et al. 2013, Orskov et al. 2014)

However, the quality of the bio-digester, bio-digester volume, and maintenance plans are not the only factors that contribute to the quantity of gas produced. Sufficient biomass for digestion, access to water and ambient temperature are all factors that can contribute to the efficiency of production. As mentioned earlier, the composition of biogas is dependent on the feedstock used during the fermentation process. Low-quality feedstock produces biogas with lower methane content, and thus lower calorific energy, whilst insufficient feedstock results in less digestible material for the bio digester's enzymes and thus a lower yield (Austin & Morris 2012, Naik et al. 2014). Access to water, which is used to prepare the feedstock can also be a significant barrier to households who do not have sufficient access to water or suffer frequently from droughts, can also negatively impact yield (Amigun et al. 2011).

One of the primary limitations of bio-digester technology is the ambient temperature of the bio-digester site (ISAT/GTZ 1999a, Bohn et al. 2007, Zhang et al. 2012). Anaerobic bio-digesters which are intended for household level installations are typically designed to operate under mesophilic conditions (20–40°C) and are best suited to temperature zones with minimal temperature variation (Bond & Templeton 2011, Amigun et al. 2011, Abbasi & Abbasi 2012). Thus rural sites with lower ambient atmosphere result in decreased biogas production (Harmon et al. 1993, El-Mashad et al. 2004, Bohn et al. 2007, Gao et al. 2012,

Zhang et al. 2012, Chen et al. 2013, Kundu et al. 2013). Studies have determined that optimal operating conditions for a bio-digester lie between 35°–40°C, however, bio-digesters continue to operate at temperatures as low as 12°C (Khan et al. 2014). Therefore, there are many regions within South Africa where the ambient temperature is sufficient to maintain the fermentation process all year round and no artificial heating is required (Austin & Morris 2012). Lastly, high investment costs remain as a significant barrier, impeding the implementation of biogas technology. Research conducted in China found that households were wary of the timescales involved with recouping the high costs of purchasing and installing a bio-digester (Jiang et al. 2011).This is especially true with regard to projects on the African continent, where high initial investment costs are compounded by limited access to credit facilities (Orskov et al. 2014).

The objective of this study was to identify upon the challenges and constraints regarding the implementation of household bio-digesters within a rural South African context.

5.2. Materials and Methods

5.1.1 Study site

The study was conducted in Machubeni, a community located in the Eastern Cape province of South Africa. Further details regarding the study site are covered in Chapter 3.

5.1.2 General characteristics of the bio-digester systems installed

Anaerobic bio-digesters come in a variety of shapes, sizes and designs and have been constructed from an array of materials ranging from extruded plastics and polymers to concrete (Hilkiah Igoni et al. 2008). Two of the most commonly used designs are the fixed dome digester and the floating cover (Bond & Templeton 2011). These bio-digesters are usually designed to operate on the human and animal waste from a single household and deliver sufficient energy to satisfy the cooking demands of this household. This translates into the average household digester having a volume between 2 m^3 and 10 m^3, producing approximately 0.5 m^3 biogas per m^3 digester volume (Akinbami et al. 2001, Omer & Fadalla 2003, Jiang et al. 2011).

Floating drum digesters are commonly made from concrete and steel, whereas fixed dome digesters are constructed with various available materials, such as bricks. Regardless of design, the fundamental principle behind these digester designs is very similar to feedstock entering the system via an inlet pipe either directly or after going through a mixing pit. This substrate is then retained and 'digested' for a period ranging from 20–100 days (Sasse 1988). The actual biogas is collected above the slurry before leaving through an outlet pipe for utilisation. Even a pit in the ground can be used as a digester provided a means for capturing the biogas is present.

Four out of the five bio-digesters installed on the site were locally designed and manufactured by Agama Energy(Agama Energy). These prefabricated units are a variation of the fixed dome design, with inspection hatches added to allow access to both the reactor chamber as well as the gas chamber (Figure 2-2: Chapter 2).

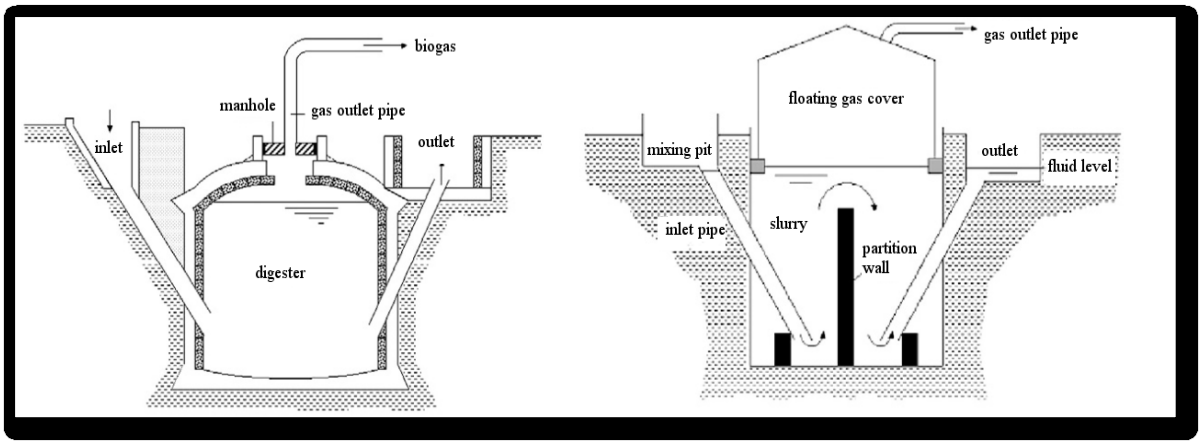

Figure 5-1: (Left) Fixed dome digester, (Right) Floating drum digester (Adapted from Bond & Templeton 2011).

The final bio-digester installed is an imported "Deenbandhu style" digester produced by Sintex in India. Notable differences between these two varieties are the ease of access and increased reactor and gas chamber volume afforded by the Agama bio-digesters (Figure 5-2). All five bio-digesters were installed at separate households with gas lines installed connecting them directly to gas-stoves.

Figure 5-2: 'Biogas Pro', 'Biogas smart Top', 'Deenbandhu' digesters (source Agama Energy).

5.1.3 Data collection

Direct field observations throughout the installation period in early 2012, coupled with monitoring over the first fourteen weeks of operation, form the bulk of this study's findings. The biogas utilized by each household was measured through the use of a standard flow meter, which measures total biogas utilized by each household. Interviews were conducted with all five households, which had been selected as trial sites for bio-digesters in early 2012. These interviews were conducted in English, with the aid of a Xhosa translator in the instances where English was not the preferred language of choice. Key players who contributed to the installation of the bio-digesters were also interviewed both before and after the construction of the bio-digesters, with ethical considerations being taken into account and surveys which were approved beforehand. Temperature data were gathered from the surrounding weather stations throughout the duration of the study and supplemented with additional readings taken from within the bio-digester itself. This was done due to the well-established inverse relationship which exists between bio-digester performance and ambient temperature (Harmon et al. 1993, Ahring et al. 2001, Lim & Fox 2011, Zhang et al. 2012, Kundu et al. 2013). The daily feeding of each bio-digester was directly monitored, and approximately 20 kg of feedstock, mixed with 20 litres of water was observed. This was then fed into the digesters. This amount was adjusted for the reduced capacity of the Deenbandhu Sintex bio-digester. The feedstock utilised by all digesters consisted primarily of freshly collected cattle dung, supplemented by additional vegetative food waste from the households.

5.3. Results

5.3.1. Factors influencing bio-digester success

Throughout the duration of the study, several key factors emerged as being critical for the success of biogas technology and were presented earlier in chapter 2 (Figure 2-4). These factors share similarities with other studies regarding the suitability and limitations of a given technology (Barry et al. 2011). The technological capacity, socio-political stability, environmental sustainability, and economic viability of biogas technology were discussed with regards to the challenges encountered in the installation and operation of the bio-digesters.

The data collected at both ambient and internal bio-digester temperature were collected at intervals throughout the study (Figure 5-3) in order to gauge the relative performance of each digester. The average ambient temperatures remain within the operating parameters of the bio-digesters installed, with a temperature range of approximately six degrees, however, this is in the lowest temperature band supported by these models around the psychrophilic (<20°C) temperature band. Despite this, the internal temperature of the digesters remained above ambient air temperature at all points.

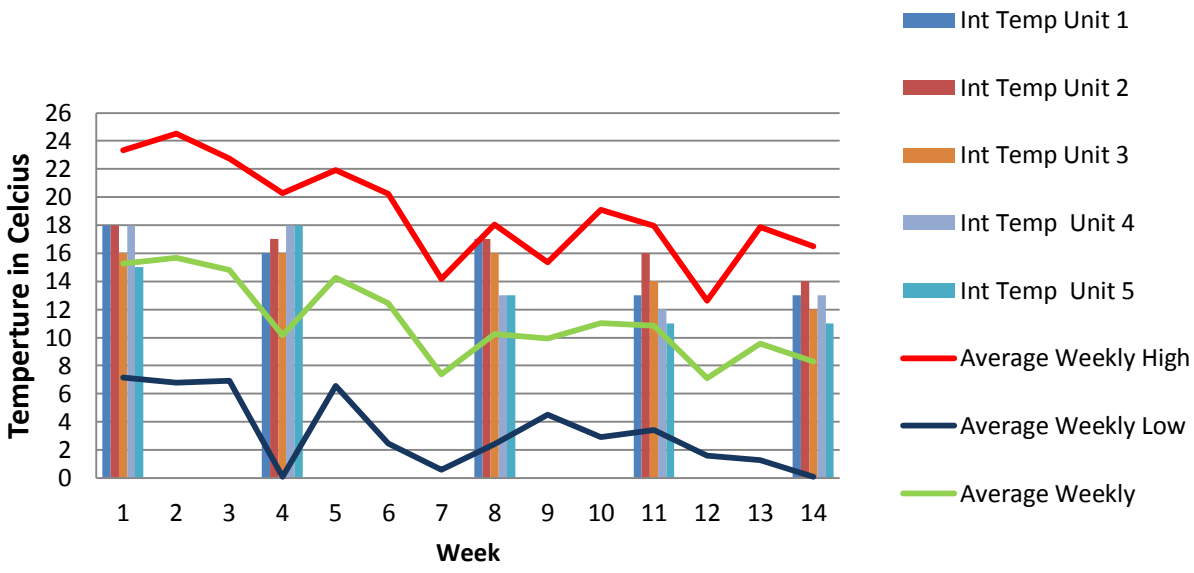

Figure 5-3: Internal temperature of all digesters over time.

The total consumed biogas by each household was plotted over time (Figure 5-4) and the comparative performance with regards to biogas produced per kilogramme of feedstock, recorded (Figure 5-5), along with the average ambient air temperature, with an overall declining trend evident as time progressed. Initially, it can be seen that the Tschamazimba bio-digester pro unit produced significantly more biogas in the initial 4 weeks, with the highest gas production occurring during week two.

The bio-digester at Boomplaas experienced technical difficulties in the final three weeks of the study and no biogas was produced after week 11.

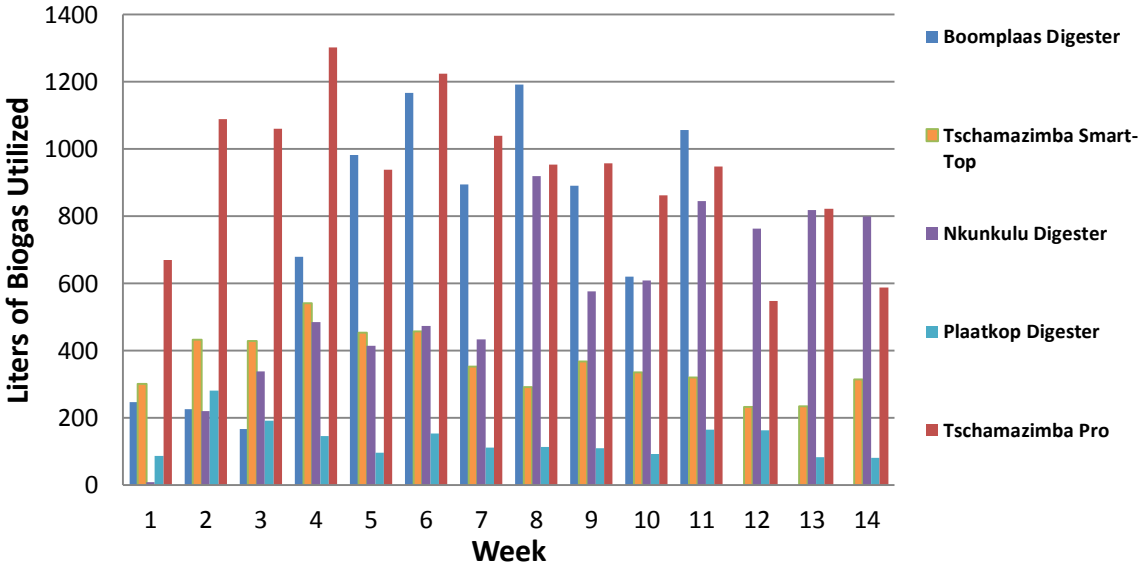

Figure 5-4: Total biogas production over study period.

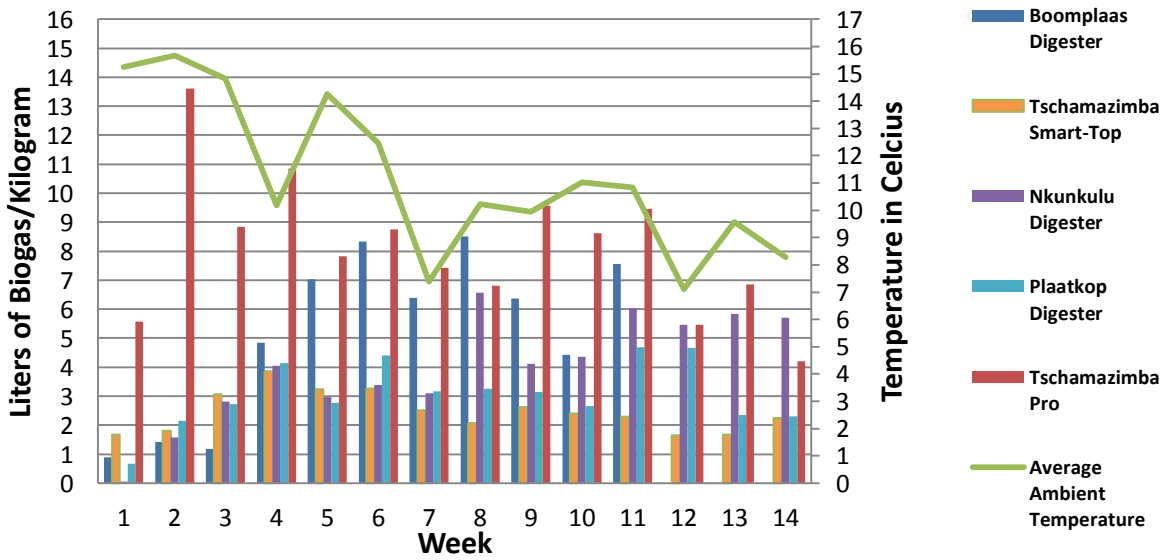

Figure 5-5: Biogas production per kilogram of feedstock.

In addition to the temperature data observed**,** a discovery was made regarding deposit build up in the digesters (Figure 5-6). After several weeks of operation, household biogas production was still below projected optimal performance operating at psychrophilic ambient temperatures at several sites. Closer inspection of the interior of the gas chambers revealed significant amounts of partially digested ligneous material, which had become trapped within the fixed dome gas storage chamber (Figure 5-7). This material had a fine porous texture and its presence within the gas chamber reduced overall gas production as excess gas, whilst also providing an artificially high measured gas pressure. It exhibited very little odour and did not have the strong smell of either the raw feedstock (manure) or the bio-slurry outflow. Despite its low weight, a significant volume of this material was removed from the reactors.

Figure 5-6: Evidence of fibrous deposit within gas chamber (Left). Figure 5-7: Closer inspection of fibrous material (Right).

5.4. Discussion

5.4.1. Technological Challenges

As mentioned previously, ensuring that the biogas digesters are capable of delivering sufficient flammable gas for daily usage is the critical factor in biogas adoption. Most technological challenges encountered, with the Machubeni bio-digesters, were minor. This was primarily due to adequate planning and the use of experienced labour, however, this is not always the case and there are numerous similarities between the challenges encountered by other projects in a variety of different countries at varying levels of development. The critical lesson learnt in South East Asia was that the standardisation of

the various biogas components leads to easier quality control and assists in ensuring that competing companies are able to work together under a single umbrella of established quality control (Mwirigi et al. 2009). This also assists in the overview of installations on a macro level and allows for more effective inspection of finished installations.

5.4.1.1. Quality of installations

All of the bio-digesters installed on the site were prefabricated units which were pressure tested before and after installation. This circumvented one of the most common implementation challenges, namely that of quality assurance (Brew-Hammond 2010, Black et al. 2011, Bruce et al. 2011), and helped safeguard against a leak occurring in either gas chamber of the bio-digester, or the pipes supplying the stove, thereby skewing the results from the start. Despite this, reactor one was offline for the final 3 weeks, which is indicative of a failure either in the installation despite having skilled technicians present, or the lack of a viable maintenance plan for rural communities. .

5.4.1.2. Maintenance plans and user training

User training and community involvement were priority aspects of the Water Research Commission project and special care was taken to ensure that households were well versed in the operation and maintenance of their bio-digesters, in an attempt to mitigate another problem facing bio-digester usage, maintenance and proper usage. After two years after installation, however, no comprehensive maintenance plan has been implemented and the ultimate responsibility for the maintenance of the bio-digesters has been placed solely upon the shoulders of the households themselves. Despite the simplicity and robust design of the bio-digesters themselves, leaks and malfunctions can arise between the outlet valve and the gas appliance. The technological capacity to repair or replace these gas lines and fittings are sorely lacking within the targeted community and are a problem endemic to the region (Amigun et al. 2011, Okello et al. 2013, Orskov et al. 2014). The Tschamazimba pro unit was seen to produce significantly more biogas initially than other reactors, and it can be surmised that that insufficient training of the local households at other sites was not sufficient to realise the true potential of the reactors. Additional instruction given to the households of Boomplass and Nunkunkulu during the course of the project can account for the increase in yield as the weeks progressed

Figure 5-8: Primary feedstock is fresh cattle dung (Left). Figure 5-9: Feedstock being mixed before addition to the bio-digester (Right).

5.4.1.3. Reduced gas production

As mentioned in the above, a large quantity of fibrous material was found in the reactors' gas chambers. It is unknown how large an impact this made on the projected yield, and how early the blockage manifested itself, but removal results in an increase in gas storage capacity. This directly translates into more available biogas and, therefore, an increased burn time and functionality for the reactors. The location of this blockage proved to be troublesome due to the importance of maintaining an air tight seal within this chamber. This was rectified easily due to the flexibility of the bio-digester design which allowed for the blockage to be cleared with minimal difficulty.

Future maintenance procedures could possibly include the inspection of the gas chamber at specified intervals by the households themselves and the matter as a whole bears further investigation.

5.4.2. Site Selection

5.4.2.1. The influence of local champions

Significant interest was generated during the pre-feasibility phase of the study as the individual households were selected and local leaders within the community invited to the sites where the technology was further explained and later demonstrated. Local champions have been established as crucial to the further development and expansion of similar projects, generating enthusiasm and sustaining levels of interest in these pilot bio-digesters. The community has developed a robust and representative network of local leaders

dedicated to assisting in natural resource conservation and rural development (Cundill & Fabricius 2010, Bolus 2009, Mwirigi et al. 2009, Jingura & Matengaifa 2009). These local champions assisted greatly in the dissemination of material regarding the operation of the biogas units and served as liaisons between the project organisers and community members at large.

5.4.2.2. Adoption of biogas technology by the community

The integration of local leaders, traditional leaders, and elected officials from the very onset of the project resulted in widespread community interest and subsequent adoption of biogas technology. Continual requests for progress reports and enquiries as to the expansion of the pilot project served as indicators of the communities desire to see the bio-digesters implemented on a wider scale. Public perceptions regarding the technology were evaluated through a widespread survey of 120 households throughout the dozen villages with over 95% of respondents indicating their desire for the digesters to be installed within their households. Despite this willingness to try the new technology, some limitations such as cultural preference will always be a factor (Mwirigi et al. 2009, Msimanga & Sebitosi 2014).

One excellent example is the manner in which 'traditional' meals are considered to be more 'flavourful' if cooked using certain varieties of fuelwood, this was also observed at Machubeni with households continuing to utilise fuelwood for the purposes of preparing certain meals (Akinbami et al. 2001). This cultural stigma remains a barrier to widespread adoption for households who exhibit luddite tendencies due to legacy cultural perceptions.

5.4.2.3. Selection of suitable sites

Three key limitations of bio-digester production are the ambient temperature, the availability of organic feedstock and access to sufficient water (Amigun et al. 2011). Numerous investigations have been conducted into optimising the methane production of bio-digesters and ambient temperature consistently appears as a limiting factor (Harmon et al. 1993, Bohn et al. 2007, Gao et al. 2012, Zhang et al. 2012, Kundu et al. 2013, Khan et al. 2014). Optimal operating conditions for a bio-digester lie between 35°-40°C, however, bio-digesters continue to operate at temperatures as low as 12° C. Due to the generally warm

climate in Africa, at most locations ambient temperature is sufficient to maintain the fermentation process and no artificial heating is required. In practice, biogas installations in Africa are based on psychrophilic (<20°C) or mesophilic (30–42°C) anaerobic digestion (Austin & Morris 2012). The loss of heat during anaerobic digestion is a direct function of the surface area and relative insulation of the digestion vessel. This results in small-scale bio-digesters losing a higher proportion of their heat than larger digesters, thereby losing efficiency (Orskov et al. 2014). This is one reason why small-scale biogas units are found in Asia and Africa but are not common in more temperate climates.

The primary concern regarding the selection of Machubeni as a study site was the low winter temperatures experienced by the region with temperatures below 0ºC in winter months. The bio-digesters were buried approximately two metres underground, partially to assist in insulating them from low ambient air temperatures. Figure 5-3 illustrates the internal temperatures experienced over the first fourteen weeks of the project. These temperatures are barely within the tolerable operating range of bio-digesters and this has had a significant impact on the gas generation potential of these units in comparison to estimated guidelines (Austin & Morris 2012)

The challenges presented by these low temperatures are offset by the abundance of feedstock in the form of cattle manure in the area. In addition to this, Machubeni has been recently connected to the municipal water network and, therefore, the challenge of water scarcity has been partially alleviated. The water requirements of bio-digesters have been highlighted before when considering the suitability of the technology in Sub-Saharan Africa, especially in water-stressed areas (Austin & Blignaut 2008, Ghimire 2013, Orskov et al. 2014). The relative performance of the various digesters in their initial fourteen weeks can be seen in Figure 5-5. This was charted against the ambient temperature of the sites.

5.4.2.4. Access to selected sites

The use of prefabricated bio-digesters decreases the risks associated with poor quality construction. It can complicate the transportation process as these units are large and unwieldy. Site accessibility remains a critical factor in the implementation of these bio-digesters. In the case of Machubeni, access to the site was limited due to a combination of extreme weather events and poor road infrastructure (Figure 5-10). These factors set back installation goals by over two weeks, resulting in increased installation costs and delayed construction . Figure 5-11 (Oldfield 2012).

Figure 5-10: Weather conditions can impact negatively upon site access (Left). Figure 5-11: Bio-digester installation delayed due to excessive rain (Right).

5.5. Conclusions

The generation of biogas through the use of household bio-digesters has great potential to assist in reducing energy poverty and assisting in sustainable development. This mature technology has been successfully implemented throughout Asia and has proven itself to be well suited towards rural applications. Despite this, it has not been widely adopted or implemented throughout South Africa. In order to accelerate this process, we need to focus on developing governmental policies which recognise the limitations of the technology and subsidise the uptake of this technology by rural households themselves.

The inclusion of the communities as a whole will be an essential component of any overarching policy and needs to be incorporated at every level. Additionally careful considerations need to be made in regards to the siting of the initial projects to ensure maximum impact and return on investment. Major factors to be considered are ambient temperature, access to the locations as well as the availability of both water and feedstock. A final consideration needs to be made regarding the standardisation of the technology and the choice of design and materials used. This will assist in ensuring easy co-operation between contractors and ensure that quality control measures are readily applicable to numerous projects with minimal re-training for inspectors.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Small scale bio-digesters as a developmental tool

Biogas technology in the form of small-scale anaerobic bio-digesters has been successfully implemented on national level in many Asian countries; improving energy access, providing sanitation, reducing indoor air pollution and assisting in food security(Gautam et al. 2009, Chen et al. 2010, Rao et al. 2010, Gwavuya et al. 2012, Poeschl et al. 2012a). This technology offers numerous benefits through the harnessing of a natural process and directly caters to the needs of populations that have remained underdeveloped and marginalised, who are heavily reliant upon their dwindling natural resources to provide for their daily needs(ISAT/GTZ 1999b, Austin & Blignaut 2008, Bond & Templeton 2011, Smith et al. 2015).. The impact of these benefits is multiplied due to the limited training required to operate and maintain a bio-digester and the time-saving potential of using biogas as an energy source versus the inefficient burning of biomass (Austin & Blignaut 2008). Another key advantage of bio-digesters is that feedstock material required is readily available in rural areas with livestock manure, kitchen scraps or even crop residues, which are all easily digested (Amigun & Blottnitz 2007, Renwick et al. 2007, Hiemstra-van der Horst & Hovorka 2009, Amigun et al. 2011, Nahman et al. 2012)

However despite its potential biogas technology has seen limited implementation at the national level within the African continent until recently. One of the most successful initiatives is the 'The Africa Biogas Partnership Programme' (ABPP). This partnership between two global NGOs (Hivos and the SVN) and five African countries (Kenya, Burkina Faso, Ethiopia, Uganda and Tanzania) aims to support the national programmes of each country and install 100 000 bio-digesters by 2017 (ABPP 2014). Currently, over 32 075 have been installed with the majority being installed in Kenya where it is quickly becoming more popular and accepted in rural areas (Ghimire 2013, ABPP 2014).

6.2 Biogas potential in South African rural households

Rural households in South Africa continue to be rapidly connected to the national grid, however despite this increased access to a more desirable and efficient energy source,

biomass usage for cooking and heating is still a regular occurrence. Socio-economic factors have limited the choices of many rural households who have coped by diversifying their energy profile. Biogas would be a welcome addition to the diverse energy pools utilised by rural households and provides numerous additional benefits in addition to increasing energy access. In this study, it was determined that the Machubeni community was very amenable towards the adoption of biogas as an energy source with most concerns stemming from the elderly who were unsure of their ability to regularly collect sufficient feedstock to ensure efficient biogas production. The current energy profiles of Machubeni, combined with the perceptions of the households indicate a desire to see this technology implemented on a much larger scale in their community.

6.3 Key Challenges

The greatest single obstacle impeding bio-digester implementation is the high initial costs associated with the installation of the device. The technical challenges currently faced by the technology primarily stem from the limited pool of trained personnel capable of installing and performing large scale maintenance on bio-digesters. This highlights the importance of adequate training and education with regards to the technology, as routine maintenance can be easily accomplished by households, resulting in longer lifespans and more efficient bio-digesters.

Temperature is also a major concern with regards to the installation of bio-digesters at higher altitudes, where climate variation has a significant impact on overall biogas production. One final major challenge hindering biogas technology in South Africa is the manner in which biogas receives little attention at the national policy level, with few goals being set and minimal funding being allocated to the development of this renewable energy technology.

6.4 Economic feasibility

With regards to investigating the economic and financial benefits associated with the implementation of bio-digesters in rural settings, a concurrent study was performed in a similar community in Kwa-Zulu Natal. This study by Smith et al. (2015) concluded that without substantial incentives offered to households, their ability to reap tangible benefits is

significantly undermined. Detailed analysis of the financial barriers currently hindering widespread implementation was also covered within this study, as covered in Chapter 2.

6.5 Recommendations

Biogas technology provides a unique suite of benefits for rural households and has the potential to drastically improve their quality of life in a sustainable manner. This technology is well established and has a proven track record and needs to be considered more seriously at the national and provincial level as a valid tool for development. Further research into the long-term benefits for South African rural households, with a larger sample size, will allow for more accurate modelling of the long-term benefits and developmental potential of biogas technology. By providing adequate financial and infrastructural support, the local and national government can provide rural households with the tools they need to build a brighter future.

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APPENDIX

Appendix 1: The financial and economic feasibility of bio digester use and biogas production for rural households.

INFORMED CONSENT

I am from Rhodes University and doing a survey on the perceptions households which have had biogas-digesters installed. We would like you to contribute to this research by answering our questionnaire on your household's use of energy, what livestock you keep and what food you grow and most importantly what effect the biogas-digester has had. Your answers are very important for our research; we, therefore, value your answers and thank you for your help and taking the time to assist us in the survey

- **All questions are for research purposes only.**
- **Participation is voluntary, and you are free to withdraw from the study *at any time*.**
- **Your participation will be highly appreciated, thank you.**

In terms of the University's policies governing research, you are requested to sign the following statement indicating your willingness to participate in this research project.

I……(full names of participant) hereby confirm that I understand the contents of this document and the nature of the research project, and I consent to participating in the research project.

I understand that I am at liberty to withdraw from the project at any time, should I so desire.

SIGNATURE OF PARTICIPANT ……

DATE ……

Questionnaire on energy sources, use and views on household biogas

BIOMASS ENERGY AUDIT QUESTIONAIRE

Date: _____ Interviewer: _____ Translator: _____

Town/area _____ Street: _____ Household number: _____
Sub-ward _____
Sample no.: _____ GPS Co-ordinates: _____

6.6 SECTION A: ENERGY USE PROFILE

A1. Which of the following energy forms does this household use? (**write the rank 1-3 of the most to least used energy forms, where a combination is used in the household*).

Energy	Use			Energy	Use		
	a) Lighting	**b) Cooking**	**c) Heating**		**a) Lighting**	**b) Cooking**	**c) Heating**
Electricity	*1*	*1*	*1*	Fire wood	*7*	*7*	*7*
Paraffin	*2*	*2*	*2*	Coal	*8*	*8*	*8*
Gas	*3*	*3*	*3*	Charcoal	*9*	*9*	*9*
Candles	*4*	*4*	*4*	Dung	*10*	*10*	*10*
Bio-Gas	*5*	*5*	*5*	Crop residues	*11*	*11*	*11*
12 V car batteries	*6*	*6*	*6*	Generator	*12*	*12*	*12*

A2. Which of the above energy forms are most important for your household?

Lighting		Cooking		Heating	

6.7 SECTION B: USE OF FIREWOOD

B1. Does your household ever use firewood? Yes [*1*] No [*2*]

*(*If No, continue to Section E)*

B2. If yes, for what purposes?

v	*1*	Heating inside the home	*2*	Heating when outside	*3*
Other (please specify):					

B3. If you cook on an open fire, where do you make the fire?

- a) In summer:	In the house	*1*	In an external cooking shelter	*2*	Outdoors	*3*
- b) In winter:	In the house	*1*	In an external cooking shelter	*2*	Outdoors	*3*

B4. If you use an inside fire, do you make an open fire, or burn the wood in a stove?

Open [1] Stove [2] Other [3]

B5. Since receiving your Bio-Gas stove do you make fire inside more often?

More often	*1*	The same amount	*2*	Less often	*3*

B6. Can you please show me how much wood you used to use in a day before the Bio-Digester was installed? (**weigh the bundle*)

_____ Kg

B7. Can you please show me how much wood you now use? (**weigh the bundle*)

_____ Kg

6.8 SECTION C: COLLECTION OF FIREWOOD (only complete this section if answer to Q B1 is yes)

C1. a) How do you usually obtain the firewood that you use?

Buy only	*1*	Collect only	*2*	Buy and Collect	*3*

b) If you 'buy and collect', do you?

Buy More	*1*
Equal	*2*
Collect More	*3*

C2. If you hardly ever collect firewood, why is that so?

Not enough available	*1*	Don't have time	*2*	We prefer to buy it	*3*	Too far away	*4*

C3. Who in the household collects the firewood?

a) Who is the main person?

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

b) Who helps?

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

C4. From where do they collect the firewood?

a) _____

b) Distance? _____*km*

C5. How long does each trip to collect firewood take you? _____*hours, minutes*

C6. Before the Bio-Digester was installed how often do you/they go to collect wood?

a) In summer _____*trips per week*
b) In winter _____*trips per week*

C7.Now after the Bio-Digester has been installed, how often do you/they go to collect wood?

a) In summer _____*trips per week*
b) In winter _____*trips per week*

C8. What tree species do you use for firewood?
(for a) *write the rank 1-3 of the most to least used tree species, where a combination is used in the household*).

Tree Species	**a) Used for firewood**	**b) Used for firewood most often**	**c) Most preferred as a firewood**
	1	*1*	*1*
	2	*2*	*2*
	3	*3*	*3*
	4	*4*	*4*
	5	*5*	*5*
	6	*6*	*6*
Other (*please specify*)			

6.9 SECTION D: BUYING FIREWOOD (only complete if answer to *Question C1* is yes to buy)

D1. Before the Bio-Digester how often did you buy firewood

a) In summer
_____*times per month*
b) In winter
_____*times per month*

D2. How much did you generally buy each time? (* *remember to record unit- ask to be shown the bundle and weigh it*) _____*kg*

D3. What was the cost? (* *remember to record the unit*) _____ *per bundle/kg?*

D4. How long did that amount usually last? _____*days*

D5. Now after the Bio-Digester how often do you buy firewood

a) In summer
_____*times per month*
b) In winter
_____*times per month*

D6. How much do you generally buy each time? (* *remember to record unit- ask to be shown the bundle and weigh it*) _____*kg*

D7. What is the cost? (* *remember to record the unit*) _____ *per bundle/kg?*

D8. How long does this amount usually last? _____*days*

6.10 SECTION E: USE OF Bio-GAS

E1. How many days a week does your household ever use the Bio-Gas?

Summer

1	*2*	3	*4*	5	*6*	7

Winter

1	*2*	3	*4*	5	*6*	7

*(*if 0 go to Section F)*

E2. If usage is greater than 1, what purposes do you use the Bio-Gas for?

Cooking	*1*	Heating water for tea	*2*	Heating inside the home	*3*	Heating outside the home	*4*
Other (please specify):							

E3. What gas appliances do you have?

Small LPG gas burner	*1*	Gas Stove	*2*	Heater	*3*	Lamp	*4*
Other							

E4. Do you receive enough gas from your digester for your needs? Yes [*1*] No [*2*]

E5. Do you ever run out of gas? Yes [*1*] No [*2*]

E6. If so what do you think is responsible?

E7. Did you receive any training in the use of the digester?

E8. Assuming that you had training, how would you rate the training?

Excellent (Understood everything and would not make any changes)	Very Good (Understood everything, but would make some changes)	Good (Understood most things, but would like to know more)
Can't Remember	Bad (Did not understand everything and would like to have a refresher course)	Terrible (Did not understand anything)

6.11 SECTION F: bIO-dIGESTER No longer in use (only complete if answer to *Question e1* is 0)

F1. Is your Bio-Digester still functioning? Yes [*1*] No [*2*]

F.2 If yes, when did your Bio-Digester cease to function? _____

F.3 What are the details regarding the failure of your Bio-Digester?

F2. If no, why is it that you no longer use the Bio-Gas?

F3. What feedstock were you using in your Bio-Digester?

F1. Overall would you rate your experiences with the Bio-Digester as positive or negative?
Positive [*1*] Negative [*2*]

6.12 SECTION G: bIO-dIGESTER Feedstock

G1. What feedstock are you currently using in your Bio-Digester?

G2. How many days a week do you 'feed' the biodigester

Summer

1	*2*	3	*4*	5	*6*	7

Winter

1	*2*	3	*4*	5	*6*	7

G2.. How do you usually obtain the dung that you use?

Collect from our own livestock	*1*	Collect from the livestock of others	*2*	Buy it	*3*

G3. *Assuming dung is used,* Where is the dung collected from? **a)** _____
b) Distance? _____ *km*

G4. How long does it take to collect the dung? _____*hours, minutes*

G5. How often do you/they go to collect dung: a) In summer _____ *trips per week*
b) In winter _____ *trips per week*

G6. How many livestock do you own?

a) Cattle		b) Goats		c) Pigs		d) Donkeys	
e) Horses		f) Sheep		g) Chicken		h) Duck/Goose	

G7. Do you keep your livestock in a kraal overnight? Yes [*1*] No [*2*]

6.13 SECTION h: WATER & FOOD SUPPLY

H1. Where do you get your water from?

River/Stream	*1*	Municipal tap inside house	*2*	Municipal tap directly outside house	*3*
Borehole	*4*	Rainwater Tank	*5*	Community stand/municipal tap	*6*
Tap from runoff water (captured from mountain)	*7*	Other *(Please specify)*			

H2. How far from the household is your water source, distance? _____ *km*

H3. How much time do you spend a day collecting water? _____ *hours, minutes*

H4. How much water do you use per day? _____ *litres (*show 20l bucket)*

H5. Who in the household collects the water?

a) Main person

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

b) Helpers (if any)

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

H6. Do you grow your own vegetables? Yes [*1*] No [*2*]

H7. Do you grow fodder for your cattle?

a) Yes [*1*] No [*2*]

b) If yes, what fodder do you grow?

Kikuyu	Eragrostis hay (bought)	Lucerne hay (bought)	Home grown legumes
1	*2*	*3*	*4*
Other			

c) If no, why don't you grow fodder for your cattle?

Don't have cattle	Don't have time	Don't have enough land	They can survive without it	Too much effort	It doesn't grow well	Can't afford to
1	*2*	*3*	*4*	*5*	*6*	*7*

H8. Do you use fertiliser for your crops/gardens/any growing you do (** make certain that fertiliser is not just considered to be bought 'fertilisers'*?

Yes [*1*] No [*2*]

*(*If NO, continue to Section H)*

H9. *If yes,* Do you use the Bio-Slurry from the Bio-Digester? Yes [*1*] No [*2*]

H10. *If yes,* Have you noticed a difference in yield since you started using the Bio-Slurry?

H11. Do you buy fertiliser?

a) Yes [*1*] No [*2*]

If Yes				
b) What fertiliser do you buy?	232 (22) NPK	232 (25) NPK	DAP	Other (*please specify)*
	1	*2*	*3*	
c) How much do you buy per <u>year</u>?				*kg per year*
d) How much does it cost you per <u>year</u>?				*per year*
e) If No, what do you use for fertiliser?				

6.14 SECTION I: Experiences oF BIOGAS

I1. How long has your household been using biofuel?

I2. What experiences have you had with biogas as a fuel? *(*ask only if the response of H1 is Yes)*

a) Advantages/good aspects	**b) Disadvantages/problems**

(* If insufficient space in table continue writing on back of page)

I3. Assuming equal prices, which energy source would you rather buy to satisfy your household cooking needs?

Firewood	*1*	Dung	*2*	Gas	*3*	Biogas	*4*	Paraffin	*5*
Other (*please specify*)									

I4. What lessons have you learned from your time using the Bio-Digester?

6.15 SECTION J: TIME SAVING

J1. Who is responsible in your household for preparing meals and the way you cook them?

a) Main person

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

b) Helpers (if any)

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

J3. Has cooking with Bio-Gas made cooking easier?

Cooking is significantly easier now	1	Cooking is slightly easier now	2	No difference	3	Cooking is slightly harder now	4	Cooking is significantly harder now	5

J2. Who is responsible for running the biodigester?

a) Main person

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

b) Helpers (if any)

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

J3. Overall have you found that the Bio-Digester has saved you time?

Have saved a considerable amount of time.	1	Have saved a small amount of time.	2	No difference	3	Have less time available	4	Have considerably less time available	5

6.16 SECTION K: HOUSEHOLD PROFILE

K1. Please give the details of anyone living in the household

1. Personal Identification number (PID)	*** Name of household member**	**2. Relation to household head[1)]**	**3. Year born** *(yyyy)*	**4. Sex** *0=male 1=female*	**5. If deceased: What year did s/he pass away?**
1	Include surname of household head	Household head = code 0			
2					
3					
4					
5					
6					
7					
8					
9					
10					

K2. Is your house electrified? Yes [*1*] No [*2*]

K3. If yes, when was it connected? _____

K4. Does your household own an electric stove/oven/hot plate?

Yes [*1*] No [*2*]

K5. How much did you spend per month on electricity before the Bio-Digester?

a) In winter? R_____ **b)** In summer? R_____

K6. How much do you now spend per month on electricity?

a) In winter? R_____ **b)** In summer? R_____

Appendix 2: Follow Up Questionnaire on energy sources, use and views on household biogas

INFORMED CONSENT

A team from the Rhodes University is doing a study on the implementation of bio digesters in South Africa. We would like you to contribute to this research by answering our questionnaire on your household's use of energy, what livestock you keep and what food you grow. Your answers are very important for our research; we therefore value your answers and thank you for your help and taking the time to assist us in the survey!

- You do not have to fill in your name
- All questions are for research purposes only. Participation is voluntary, and you are free to withdraw from the study at any time.

In terms of the University's policies governing research you are requested to sign the following statement indicating your willingness to participate in this research project.

I……(full names of participant) hereby confirm that I understand the contents of this document and the nature of the research project, and I consent to participating in the research project.

I understand that I am at liberty to withdraw from the project at any time, should I so desire.

SIGNATURE OF PARTICIPANT ……

DATE ……

BIOMASS ENERGY AUDIT QUESTIONAIRE

Date: _____ Interviewer: _____ Translator: _____

Town/area _____ Household number: _____

Sub-ward _____

Sample no.: _____ GPS Co-ordinates: _____

SECTION G: WATER & FOOD SUPPLY

G1. Where do you get your water from? (**rank 1-3 from most to least used source, where water is obtained from more than one source*)

River/Stream	*1*	Municipal tap inside house	*2*	Municipal tap directly outside house	*3*
Borehole	*4*	Rainwater Tank	*5*	Community stand/municipal tap	*6*
Tap from runoff water (captured from	*7*	Other *(Please specify)*			

mountain)			

G2. How far from the household is your water source, distance? _____ *km*

G3. How much time do you spend a day collecting water? _____ *hours, minutes*

G4. How much water do you use per day? _____ *litres (*show 20l bucket)*

G5. Who is the main person in the household who collects the water?

Men	*1*	Women	*2*	Boy child	*3*	Girl child	*4*

G6. Do you grow your own vegetables?

Yes [*1*] No [*2*]

G7. Do you grow fodder for your cattle?

a) Yes [*1*] No [*2*]

b) If yes, what fodder do you grow?

Kikuyu	Eragrostis hay (bought)	Lucerne hay (bought)	Home grown legumes
1	*2*	*3*	*4*
Other			

G8.

a) Do you use manure for your crops or vegetables (*

Yes [*1*] No [*2*]

b) Do you use fertiliser for your crops or vegetables?

Yes [*1*] No [*2*]

*(*If NO, continue to Section H)*

G9. Do you buy fertiliser?

a) Yes [*1*] No [*2*]

If answer to G9. a) is YES, ask following questions:					
b) What fertiliser do you buy?	232 (22) NPK	DAP	231 NPK	Lime	Other
	1	2	3	4	
c) How much do you buy **per year**?	*kg*	*kg*	*kg*	*kg*	*kg*
d) How much does it cost you **per year**?	*kg*	*kg*	*kg*	*kg*	*kg*

SECTION H: PERCEPTIONS OF BIOGAS

H1. Have you heard of biogas Yes [*1*] No [*2*]

H3. What are the good things that you have heard about biogas and what are the bad things that you have heard about biogas? *(*ask only if the response of H1 is Yes)*

b) Advantages/good aspects	**b) Disadvantages/bad/problems**

(* If insufficient space in table continue writing on back of page)

*(*A detailed explanation must be given about biogas at this point – see supplementary information & pictures.)*

H4. If all the cooking energies cost exactly the same amount of money, what source of energy would you choose for your household cooking needs?

Firewood	*1*	Dung	*2*	Gas (LPG)	*3*	Biogas	*4*	Paraffin	*5*	Electricity	*6*
Other (*please specify*)											

H5. Would you be happy to use biogas for cooking? Yes [*1*] No [*2*]

H6. If a biogas system is installed at your house how much would you be willing to pay for the gas if sufficient gas is provided to replace ALL your cooking needs and you get fertiliser from the digester to use on your food garden and fodder crops? (**this is hypothetical, make sure they know that this will not influence how much they may be charged if a biodigester is given to them in the future*)

R _____ *per month*

SECTION I: PERCEPTION OF HOUSEHOLD BIODIGESTERS AND SUITABILITY REQUIREMENTS

I1. If your household could run a biodigester that can give you biogas for cooking and fertiliser, would you want to have one?

Yes [*1*] No [*2*]

*To run a biodigester and get biogas, it is required that you feed it with 20kg (two 20l buckets [*show bucket]) of dung and 20l of water every day.*

I2. Would your household be willing to do this?

Yes [*1*] No [*2*]

I3. Does your household own cattle?

Yes [*1*] No [*2*]

How many cattle?			