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An investigation of the potential and the limitations of small-scale biogas in urban Africa

A revised dissertation submitted for the degree of Philosophiae Doctor

by

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Dedication

For my father,

who willingly gave up so much to give me an opportunity.

Thank you for teaching me to be a scientist.

Declaration

I, Linus Naik, hereby declare that the work on which this thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university. I authorise the University of Cape Town to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

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Linus Naik

23rd October, 2019

Synopsis

Continuing urbanisation in Sub-Saharan Africa provides many development challenges including; energy provision, waste management and sanitation. On-site biogas has the potential to provide renewable energy to meet energy needs, whilst also addressing waste management and possibly sanitation. In urban settings, up to 50% of the municipal waste in urban can comprise organic waste which typically remains an untapped energy source, while the total waste volume continually increases with population growth. Whilst some countries (including Ethiopia and Uganda) have support via national government and/or foreign investment for biogas deployment, their focus is on rural biogas for agricultural waste, not urban biogas for municipal waste. This thesis investigates the case for small-scale biogas as a technology to assist sustainable urban development through understanding factors which will ensure operational success to safeguard investment. The factors investigated were productivity, stability and the need for remote monitoring. The research was divided into three distinct phases which occurred chronologically.

The first phase was observational and developmental, in which one biogas unit in a semi-controlled environment was monitored. Some initial insight into the factors which caused instability (in this case, the addition of simple carbohydrates) as well as two methods of mitigation of instability (namely addition of lime and a cessation of feed) were noted for future investigation. Also, in this phase, a mobile phone application, called the “Biogas Monitoring Tool” was developed and refined, accompanied by a monitoring methodology to collect information on measured variables which were considered to inform productivity and stability of small-scale biogas units. Of the variables mentioned, the laboratory method of evaluation of two in particular (pH and temperature) was replaced with more practical and rudimental measuring techniques. The appropriateness of the replacements was statistically analysed, evaluated and found to be acceptable for the intended purposes.

The second phase of research involved the widespread rollout of the Biogas Monitoring Tool developed in the first phase. The platform was used to gather data from ten small-scale biogas units across southern Africa to further investigate and analyse the factors which affected the productivity and stability of small-scale biogas units. Readings of pH, burn time, pressure, mass and type of feed were captured through the Biogas Monitoring Tool over twelve months. The analysis showed episodes of instability of biogas units linked to changing feeding regimes of simple carbohydrates, organic loading rates as well as changes in feed ratios and frequency. In terms of productivity of the biogas units, seasonal fluctuations in the five units which were monitored over the winter months was evident, as well as potential underutilization of biogas produced. Furthermore, it was noted that there was better utilisation of gas for institutional installations compared to domestic installations. It was also shown that in five of the biogas units, the stability of the unit had an influence on the quality of gas produced, and it was indicative that it had an influence on the quantity of gas produced.

For the third and final phase of research, theories developed from insight gleaned in the second phase were tested on one biogas unit in a controlled environment. There were three sets of experiments conducted on this unit which had a pre-determined feeding regime. Also, the biogas stove was burned daily until the biogas ran out, to quantify the productivity of the biogas unit. Firstly, a stepwise addition of the organic fraction of municipal solid waste was introduced into the feeding regime. In this case, it was demonstrated that the organic fraction of municipal solid waste can in fact be the sole feed-stock for biogas unit, with the proviso that there was appropriate knowledge support which includes quick mitigation strategies for periods of instability. Secondly, the effect of pre-treatment of the organic fraction of municipal solid waste was investigated. It was found here that the pre-treatment did appear to improve the stability of the biogas unit, a consideration which may be significant for potential widespread adoption of the technology. Finally, the effect of temperature on gas production was confirmed and quantified, with higher average temperatures showing higher gas production.

In conclusion, it was found that all the small-scale units which formed part of this research showed episodes of instability. When considering this technology for energy provision for urban development, there are important considerations around feedstock variability by way of feed type, volume, and frequency affecting the stability of these units. With reference to productivity, it was shown, not only that temperature naturally does affect gas production, but also that the productivity is linked to the stability. Furthermore, it was deemed that the type of setting (institutional versus domestic) was in fact more significant than the ambient temperature or the feeding regime when considering gas use and gas utilisation as indicators of productivity. Finally, with regard to knowledge support via remote monitoring, it was shown that simple and practical measurements were able to provide insight into factors which affected productivity and stability of small-scale biogas units. The final phase further utilised the remote monitoring tool to actively manage the operation of the biogas unit and quickly mitigate instability.

Thus, small-scale biogas has the potential to be adopted as technology for energy provision in urban development. The limitations of the application are that waste-based biogas would meet only an portion of the total energy requirement in any particular urban area and that based on the findings of this research, all units are subject to periods of instability. There are various mitigation strategies for instability, some of which involve active management, which may be supplied remotely.

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Foreword

In my initial foreword, I had highlighted the advent of commercial biogas technology in Southern Africa. In this regard, there was mention of some organisations promoting the adoption of waste to energy, (particularly biogas) and my own involvement in some of them. These are now quite dated as the examination of the original thesis took just over fifteen months, meaning that two years have passed between the original thesis and this revised submission. Therefore, in line with the revisions made to the body of the thesis, I have replaced the original foreword with a revised one. With reference to the thesis itself, I have gone into detail on the changes made and reasons for them in a separate document. Here, however, I would like the take the opportunity here to make a few relevant comments on some developments in the biogas and energy space over the last two years.

In March 2017, at the time of the original submission, the New Horizons Energy plant was being commissioned in Cape Town. It was to become the second large-scale commercial biogas plant and the first commercial urban biogas plant in South Africa. It was also the first plant to have the organic fraction of municipal solid waste as an anchor feedstock. The plant opened in late 2017 but has since closed its doors in mid-2018. However, in late 2018, a small-scale unit was commissioned at a shopping centre in Cape Town – N1 City. This unit is monitored remotely (an aspect explored in this thesis) from the Netherlands. In my initial foreword, I had concluded with note for a case to be made for smaller decentralised facilities, and the N1 City unit, while still a demonstration plant, it is an interesting application at an institutional level.

In 2017, it was envisioned that the energy climate in South Africa would start changing to accommodate more renewables into the energy mix. However, the country still has a heavy reliance on coal and the crunch has started to yet again become felt. This thesis should provide an insight into the potential and limitations of small-scale biogas to meet such energy needs in urban Africa.

– Linus Naik, June 2019

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List of abbreviations

AW	Agricultural Wastes
BMP	Biochemical Methane Potential
CoCT	City of Cape Town
E&PSE	Environmental & Process Systems Engineering
EC	Eastern Cape
EM	Effective Microbes
GDP	Gross Domestic Profit
KZN	KwaZulu-Natal
LCF	Local Composting Facility
LIM	Limpopo Province
LPG	Liquefied Petroleum Gas
min	minute
MDGs	Millennium Development Goals
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
S	Sewage
SDGs	Sustainable Development Goals
SWZ	Swaziland
UCT	University of Cape Town
UN	United Nations
WC	Western Cape

List of symbols

°C	degrees Celsius
$Ca(OH)_2$	calcium hydroxide a.k.a. lime
CH_4	methane
C:N	carbon to nitrogen mass ratio
CO_2	carbon dioxide
e	energy rating
H_2	hydrogen
hr	hour(s)
J	Joules
K	Kelvin
kg	kilograms
kJ	kiloJoule
kPa	kiloPascal
kW	kiloWatt
m^3	cubic metres
mol	mole(s)
n	number of moles
ñ	molar flow rate
mV	millliVolts
P	pressure
PJ	petaJoule
R	rate constant for ideal gases
sec	second(s)
T	temperature
V	volume

Chapter 1: Introduction

It is widely recognized that access to, and supply of modern energy play a key role in sustainable development. Rapid increases in urbanisation, particularly in the African context, demand the need for sustainable urban development. Biogas technology presents a possible solution which can be utilised on a small-, medium- or large-scale and has the potential to work in the growing urban populations of Africa as both an energy production and waste management technology. This introduction will provide the information which postulates the potential and the limitations of biogas, and in particular, small-scale biogas units as a suitable technology for addressing some of the needs created by rapid urbanisation in Africa.

1.1. Urbanisation in Africa and the need for technologies

As a global phenomenon, urbanisation is a relatively new concept. Just over a century ago, only 5% of the world's population lived in cities. The advent of the 20th century saw a marked increase in rural-urban migration (Njoh, 2003). The world's urban population has increased from 150 million to 2.2 billion since 1900, an increase from 15% to 50%. This has been backed up by population statistics from the United Nations (UN, 2014) stating that over half of the world's population now officially lives in urban areas. Asia and Africa, and in particular, Sub-Saharan Africa, remains the least urbanized in the world, yet at the same time, the rate of urbanisation is the highest in the world. The report goes on to state that by 2050, it is projected that Africa will move from having 40% to 56% of its population living in urban areas. African cities are often experiencing population growth rates two to three times more than those of their countries. The continent's urban population is projected to double every 12 years (Kamete, *et al.*, 2001). This has placed a strain, particularly on local governments, with respect to provision of goods and services, and illustrates the pressures and considerations caused by urbanisation and the need to manage resources carefully. The strain is intensified by high concentrations of the poor in urban areas and the inadequate management of technical skills (UN, 2005).

Two important aspects are those of energy provision and waste management, presenting the challenge that urban areas be developed in a sustainable manner. An extract from Mark Swilling on his work in “Local governance and the politics of sustainability” provides useful context in which sustainable urban development is framed in Sub-Saharan Africa: “Sustainable urban development has become a buzzword but rarely is it adequately defined. Many problems that are rooted in unsustainable resource use approaches are now top of the agenda in many African municipalities, for example, traffic congestion, rising water and energy prices, declining food security, rapidly rising building costs, shortage of landfill space, polluted rivers, degraded environments and over-flowing sewage treatments” (Swilling, 2008). In addition, the Sustainable Development Goals (SDGs) which now supersede the Millennium Development Goals (MDGs) (which were current at the inception of this thesis), now have goals directly tailored towards sustainable urban development. The SDGs provide a useful and generally agreed upon policy direction with which local governments could align their efforts to address the above-mentioned challenges.

In particular, the SDGs talk towards energy provision and sustainable human settlements (UN, 2016). The SDG’s themselves are all listed in Appendix A and contextualise the challenges facing sustainable development. Of particular relevance in this context are Goals 7 and 11, listed as follows:

- Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all
- Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable

While more developed countries have witnessed the start of discussions about the possibility of “prosperity without growth” (Jackson, 2009) and even towards “sustainable degrowth” (Schneider, et al., 2010) (full definitions in Appendix B), cities of the global south are faced largely with slum type urbanism which poses different problem set and primarily implores the provision of basic human needs by local governments. More recently, there has been substantial research into the theory, economies and politics of sustainable urban development through advanced local energy planning. Technology plays a key role in sustainable development and identifying the appropriate technology for its purpose would be a stand-alone investigation, but perhaps, it is useful to first define the role of technologies in sustainable development. This is illustrated using the well-known IPAT equation (Ehrlich & Holdren, 1971) shown as follows: **Impact = Population x Affluence x Technology**.

Using the example of carbon emissions, it is apparent that if population and affluence keep increasing, then in order to stabilise the impacts, the technology must counteract (example presented in Appendix C). From an energy perspective, renewable energy and energy efficiency address the role of technology through:

- dematerialisation – using less resources to produce the same energy service
- substitution – using renewable energy instead of carbon intensive ones (Robert, *et al.*, 2002)

In Europe, the installed power production capacity in 2008 based on several sources was as follows: natural gas (18%), oil (6%), coal (26%), nuclear (33%), hydro (12%) and other renewable (3%). The current trends in power production point to an increased use of natural gas and renewables, slight increase in nuclear and decrease in coal and oil consumption (Afgan & Carvallo, 2008). Two factors were expected to influence future trends in the European energy sector (Hemmes, *et al.*, 2007): the need to meet the Kyoto commitments and the issue of security of energy supply, reflected in the green paper: “Towards a European Strategy for the Security of Energy Supply”. The authors go on to stress the importance of multi-source, multi-product energy technologies; their work is a prominent example of how the European Union is trying to meet its challenges by innovating its way out of dirty energy (Jacobsson & Bergek, 2004); investing heavily in research and innovation since the 1980s (Suurs & Hekkert, 2009). Since 2010, however, it has been proposed that working with technologies in the African setting may be significantly different to working with technologies in the European Union (Sovacool, *et al.*, 2015). One of the attributed reasons for this is the that there is now an extensive inventory of available developed technologies, yet a dearth of application. Thus, it has been argued that the African focus should be on developing the ability to choose and deploy suitable technologies rather than on developing new ones (von Blottnitz & Chakraborty, 2006).

1.2. A case for biogas as the technology of choice

In the last few decades, there has been a significant non-sustainable use of fossil fuels which has necessitated research into renewable energy sources and technologies. This, in part, has led to increased awareness into the availability and accessibility of such technologies, significantly since the 1970s oil crisis (EOCD, 1985). Biogas is a renewable energy source which has been practiced for centuries and represents a potentially viable option for the future. It is produced via anaerobic digestion in biogas units with two main outputs, a methane rich gas (which is an energy source) and a digestate (which is a nutrient source). Biogas units may be used as a treatment for many organic products and waste streams, from food crops (such as maize) (Dutt, 1992), to organic fraction of municipal solid waste, animal manure (Balasubramanian & Bai, 1992) and even wastewater (where it was commonly used as a method of reducing the organic loading) (Elango, *et al.*, 2007). Thus, biogas units have a variety of designs and applications, ranging from small to large-scale operations, and even one- and two-stage processes (Aslanzadeh, et al., 2014). In this thesis, small-scale is defined as units at a household or institutional level, having no more than 20 m^3 total capacity.

Biogas production via anaerobic digestion has been noted to have been practiced for centuries, so in a sense it is not a new technology, but has more recently been identified as an important renewable energy source (Surendra *et al.*, 2014). Thus, the technology itself and the factors which affect its effectiveness have been well researched. For example, the impacts temperature, pH, organic loading rate, carbon-to-nitrogen ratios, microbial populations and hydraulic retention time have all been identified to have an effect on biogas operation (these are all discussed further in Chapter 2). Large-scale units would naturally be centralised and need to be commercially viable and ensure operational success to attract investment. In Europe and Asia, there has also been widespread rollout of small-scale biogas systems, which would be decentralised and have the added advantages of energy generation on site – with a concomitant saving on transport (and associated carbon emissions). Thus, biogas may be seen as a multi-purpose solution, as it provides a renewable energy source with a waste management (and possibly a sanitation) solution and may be used to address some of the issues facing the growing urban population of the developing world (Surendra *et al.*, 2014).

The following has been taken as a summary from a review paper on small-scale biogas. “As a technology, it possesses highly attractive attributes, particularly when considering renewable energy options.

- It is a renewable energy technology that produces a multi-purpose fuel that can be used to produce domestic or industrial heat, electricity or stationery and motive power (e.g. for water pumps and transportation).
- It can often replace fossil fuels in provision of energy, thereby reducing greenhouse gas emissions
- It has the potential to address a portion of municipal solid waste problems which include landfilling and its associated land availability issues and concomitant greenhouse gas emissions
- A by-product of the process is the digestate/effluent, which contains liberated nutrients, specifically nitrogen and phosphorus, which make it potentially useful for soil application as a fertilizer.” (Naik, *et al.*, 2014)

However, as mentioned, much of the research and rollout of small-scale biogas has been in done in Europe and Asia, both of which now boast millions of small- to medium-scale installations (Deng, *et al.*, 2017). In Africa, where there is a definite need of on-site energy generation has not experienced the same level of deployment. In a few countries (initially Kenya, Uganda, Ethiopia at the onset of this thesis, and since then Tanzania, Rwanda, Cameroon, Burkina Faso and Benin (Roopanarain & Adekele, 2017)) there are partnerships with governmental departments and technology companies in European countries (usually German or Dutch) to facilitate the deployment of the technology in appropriate rural settings via micro-financing and government grants/support. However, the operational knowledge around the productivity and the stability of such installations does not appear to be retained by the local governments or translated into wide-spread roll-out of the technology.

Thus, it appears that biogas, and in particular, small-scale biogas is a technology which is fit for purpose (Balat & Balat, 2009) but lacks understanding and knowledge support which would facilitate wide-spread deployment, particularly in urban Africa where the energy is needed.

1.3. Problem statement

Primarily, in response to the observation that access to energy services plays a pivotal role in sustainable urban development, it is noted that decentralised, small-scale biogas installations represent a technological intervention. However, such installations may come with their own set of challenges by way of ensuring productivity and stability.

Therefore, it is necessary to understand the factors which influence the operation of small-scale biogas units, and to provide appropriate knowledge support for the system to ensure operational success and safeguard any potential investments. This presents two unique challenges. The first would be to understand factors which specifically affect small-scale units which are currently in operation. The second would be to see whether there are any differences when these units are operated with typical feedstocks from an urban setting. Both these would tie in to providing the necessary knowledge support, and possibly informing an effective monitoring system.

1.4. Research objectives

The overarching objective of this thesis is therefore to develop new knowledge to inform the potential for, and limitations of small-scale biogas, as a technology for deployment in urban Africa, specifically:

1. To advance the understanding of operational stability, the factors which influence it and potentially how to mitigate instability.
2. To quantify the gas production from substrates and determine initially whether it is dependent on the stability of the biogas unit, and secondly, determine the factors which influence it.
3. To develop and test the appropriateness of knowledge support systems for small-scale biogas units deployed in an African setting.

1.5. Thesis outline

Following on from this introductory chapter, this thesis goes on to review relevant literature from the academic sphere in Chapter 2. Since anaerobic digestion itself is an old technology, there is significant relevant literature on biogas and anaerobic digestion, so it is important to only highlight information, which is pertinent to this study, and to be concise with peripheral, but applicable topics. Given the objectives, the first task in the literature review is to understand biogas as a technology in the context of establish its intended applications. The scope is first narrowed to an African context, and then furthermore to an urban context in Africa, focusing on its unique set of challenges. There is, then, a detailed discussion and analysis of the factors which have been identified to affect the productivity and stability of small-scale systems, as well as a venture into the required knowledge support which may be required to sustain the widespread deployment of such systems. The summary of the current state of knowledge is distilled through the objectives to formulate hypotheses and develop a methodology, in that the findings from Chapter 2 are used in Chapter 3 for research formulation.

Chapters 4, 5 and 6 are results chapters in which various aspects of the thesis have been completed, analysed and discussed in context relevant to the research objectives in this introductory chapter, and the hypotheses in Chapter 3. Chapter 4 is the initial field investigation conducted on the UCT biogas unit. This study ventures initial learnings on productivity and stability of one small-scale system, noting potential mitigation strategies for instability. At the same time, the remote monitoring methodology is developed, refined and analysed by way of comparisons of various monitoring techniques. Chapter 5 is a remote monitoring study, which uses the new developed and refined monitoring methodology on a widespread application, to collect and analyse real data from ten small-scale biogas systems around Southern Africa. The purpose of using the monitoring methodology was two-fold; firstly, to gain insights into productivity and stability of small-scale biogas units through reported parameters; and secondly, to test the effectiveness of the remote monitoring methodology. In Chapter 6, one small-scale unit, installed at a composting facility was actively managed to run test work to further inform theories on stability and productivity which had been developed after the monitoring study in Chapter 5. Key outcomes of the results chapters are consolidated and synthesised in Chapter 7, to re-address the research objectives, the problem statement and the hypotheses. Some recommendations are then made for future work with an outlook on the scene for small-scale biogas in urban Africa.

The intention of this thesis was to propose contexts for where small-scale biogas units could be successful as a technology in urban Africa, and to identify the knowledge support needed to safeguard new infrastructure investment. Firstly, observational analysis was used to gain initial insight and then build and deploy a monitoring methodology. This is then deployed and used to gather data on a wide-scale to further inform operational productivity and stability. Lastly, theories generated from the insights are tested on one final biogas unit to reach more confident conclusions. Two unique contributions are attempted in this work. The first is using monitoring and operational experience to propose a knowledge support system which could safeguard investments into such a technology. The second, is the various mitigation techniques for instability to ensure operational success of small-scale biogas units.

Chapter 2: Literature Review

This chapter unpacks the current body of knowledge around relevant aspects of this thesis. From Chapter 1, the need for technologies to meet the growing energy demands of urban Africa. In this light, the first section broadly contrasts biogas against other technologies fit for the same purpose. From here, small-scale biogas is reviewed from an economic and then from an operational standpoint, before looking at the current waste management practices in urban Africa and the finally the unique challenges which may affect urban biogas installations. Findings from all these are discussed and summarised from the standpoint of the potential and limitations of small-scale biogas in urban Africa. The findings are then distilled through the objectives to inform the methodology for research in Chapter 3.

2.1. Biogas compared to other technologies

In this context, particularly on the small-scale, biogas would be used to meet primary energy needs; namely cooking, and then heating and/or lighting. Other renewable competitive technologies in the same context would be solar cookers and efficient wood-stoves for cooking; and then solar heaters and possibly photovoltaic cells for heating and lighting. Efficient wood-stoves would use the same fuel, namely wood, just less of it. Therein lies both the advantage (in that it would be market compliant as it uses the same fuel) but also the drawback (in that that using the same fuel means that any problems associated with burning wood will still be there – in this case, health issues associated with burning wood) would still be there, just less pronounced). For solar cookers, the advantage is that it is the cleanest of the technologies. However, the drawback, and the issue which may be a critical flaw to using the technology, is that it depends largely on an energy source which cannot be ensured. If being used to meet primary energy needs (as it indeed is in this context) then the cooker may simply not work on overcast days and can therefore not be used to replace traditional wood stoves. Additionally, the meal cooking efficiency is typically less than other technologies.

Biogas is certainly a more complex technology and comes with its own set of challenges and concerns when considering the context of meeting primary energy needs in urban Africa. More complex technologies are not necessarily more appropriate. Indeed, it has the added advantage of addressing a waste management challenge, something that the other two technologies do not offer. However, the complexity may arise through the need for knowledge support and skill in the operation and handling of the gas. Also, although it may have been an old technology on the whole, it is a relatively "new" technology in the proposed application, meaning that there are cultural and market compliance concerns. Finally, the high capital cost of a biogas unit is a major drawback of the technology. Skills or knowledge support may be needed to manage operations and health and safety concerns would need to be addressed to ensure operational success. Additionally, there are high capital costs associated with the technology and a need for existing infrastructure, so deployment in the informal sector may be less feasible. These details of these considerations are out of the scope of this thesis. However, they are explored in detail in the energisation study, presented as a stand-alone annexure to this thesis.

2.2. A further look at biogas as the technology of choice

It was mentioned in Chapter 1 that biogas has been well established in parts of Europe, especially Germany (Negro & Hekkert, 2009) and Asia (Rees, 2005), especially China (Deng, et al., 2017), where small- to medium-scale installations exist in the millions (Polpraset, 2007). However, as a technology, it has seen very limited deployment on any scale in Africa. At the start of this thesis, in 2011, there were only about 40 installations in South Africa (Boyd, 2010), the majority of which are rural, small- to medium-scale operations. Over the last five to six years, this has increased to just under 400 (Roopanarain & Adekele, 2017), two of which are commercial scale, with the balance being largely rural and small- to medium-scale.

The differences between urban and rural biogas units are investigated in detail later in Section 2.6, but at this stage attention must be drawn to the potential difference in feedstock between urban and rural biogas units in Africa, and indeed in commercial and personal application in places where biogas deployment is abundant. In Europe, biogas production has been incentivised and food-crops are often used as feed because they have very high biogas yields. In developing countries, this is typically not supported, for example, the Department of Energy in South Africa will only support water efficient and non-food-based crops since the country has limited arable land and is water scarce (ENS Africa, 2015), so the majority of biogas is waste based. From an energisation angle, this is advantageous, as it allows the technology to not only meet energisation needs, but also those of waste management, and possibly sanitation. Particularly in the context of municipal solid waste management, organic waste constitutes 40 – 85% of total domestic waste and is currently insufficiently utilised as an energy resource (Abraham, *et al.*, 2007). At the start of this thesis, the example was taken of the City of Cape Town (CoCT) in 2011, where the OFMSW has a high moisture content (40-80%) (Munganga, *et al.*, 2010) rendering technologies such as mass burn incineration unsuitable. Upon analysis in 2011, the waste generation to landfill in the CoCT had peaked at 2.8 million tonnes per annum in 2007/8, and although it had previously declined to some 1.8 million tonnes per annum in 2008/9 (CoCT, 2010), there remains a shortage of landfill space (Engledow, 2007). Given the current organic fraction of municipal solid waste (≈50%) produced in the CoCT, biogas was calculated to have the potential to meet between 4% and 5% of the energy needs of the city (based on a simple calculation presented in Appendix D) while at the same time reducing waste to landfill by 50% through using centralised biogas from waste generation. Anaerobic digestion was therefore postulated as the priority treatment option for the organic fraction of municipal solid waste (OFMSW) due to the advantages stated above, and indeed, this was attempted to prove itself true (at least on the large-scale) with the initial commissioning of the New Horizons Energy biogas plant which can process 500 tonnes per day of MSW (EngineeringNews, 2017). This plant has since closed as it ran out of capital before all parts could be fully commissioned.

The example given is for a large centralised facility. If a large-scale plant can only meet 5% of the energy demand of the city, the question arises as to how much of the energy demand of a household that small-scale biogas would meet. This would depend on the amount of waste that the household produced, and so the question then becomes whether or not a household produces enough waste to potentially meet its own energy demand through biogas production.

2.3. Current energy and waste management practices in urban Africa

Urban areas in Sub-Saharan Africa are faced with the challenges of appropriately accessing energy and managing their organic waste. Traditional fuels for energy (i.e. coal, paraffin and biomass) have associated health, safety and environmental impacts, as does the improper management of waste (in particular, organic waste). The demands of the urban areas and the associated waste are also markedly different to those in rural areas. The key feature is that the vast majority of the organic fraction of municipal solid waste (OFMSW) produced or generated in urban areas throughout Africa is disposed of in landfills or dumps and not further utilised aerobically nor anaerobically (Kasozi, *et al.*, 2010). In landfills, the OFMSW will degrade anaerobically to produce methane gas which is not extracted and is emitted straight into the atmosphere. In the last ten years, there have been urban composting initiatives in Kenya, Malawi and South Africa (Scheinberg, *et al.*, 2011) while in the rural setting, there has been anaerobic treatment of agricultural waste on a large scale. The government programmes for anaerobic digestion, (usually with a European sponsor) have been mentioned in Section 1.2. These programmes followed widespread rollout in Asia, particularly China, India and Nepal which have over a hundred million units between them, deployed over the last 30 years (De Clercq, *et al.*, 2017). This makes the case that there is space for widespread rollout in Africa and that, with government local energy planning, there can be structured rollout of biogas in urban Africa if the technology is proven to be fit-for-purpose.

A further look into the potential valorisation of OFMSW is discussed as follows. If valorised, biological treatment the predominant option due to the nature of the waste. Biological treatment can be classified into aerobic and anaerobic. Aerobic valorisation is usually composting, while anaerobic would be microbial fermentation in a biogas unit, or alternatively with effective microbes, now commercially found in Bokashi to produce a pre-compost which can either be applied directly to soil, or used as a pre-compost (Swilling, *et al.*, 2015). Bokashi treatment has been used in a pilot study in informal settlements (von der Heyde, *et al.*, 2014), as an organic waste management tool.

Bokashi is the term given to the Bokashi bran, as well as the treatment procedure. The treatment involves the layering of organic waste with Bokashi bran (which is wheat or oat bran sprayed with effective microbes). On a small-scale, this would be done in five or ten litre plastic drums, and on the commercial scale, it would be performed in 210 dm^3 drums. In all cases, the container would be sealed for ten to fourteen days to allow the fermentation to occur (Earth Probiotic, 2018). The resulting mixture is a valuable pre-compost. In the case of the study at the informal settlement, the treatment was found to be effective, with the observation of rodent and fly reduction, but was not cost effective due to the cost of the Bokashi Bran. The resulting Bokashi treated waste was not utilised further (e.g. in composting), but rather collected and disposed of as the intended purpose was for hygiene and sanitation.

Comparisons have been done between these treatment methods under the factors of cost, energy and greenhouse gas emissions. It was found that anaerobic treatment typically requires a larger investment (Mata-Alvarez, 1999), while from an energy balance standpoint, it was found that anaerobic treatment has a better energy balance as well as lower associated carbon footprint (Edelman, *et al.*, 2005). The latter went on to propose that in some cases, the two are combined for optimal results, in the fashion of anaerobic digestion followed by aerobic composting of the digestate. In Sub-Saharan Africa, OFMSW and agricultural wastes have been treated aerobically to produce compost which has been used mainly in the rural setting, but also in some urban farms (Scheinberg, et al., 2011) Some examples of urban composting are in Nairobi, Kenya where a food delivery company used reverse logistics to collect OFMSW for composting, and in Lilongwe, Malawi, where a community driven project collected OFMSW for an urban farming application. However, despite seeming to be simple and cost effective, aerobic treatment is not used widely in Sub-Saharan Africa (Vogel & Zurbrugg, 2008).

Anaerobic digestion on the small-scale is becoming increasingly popular in rural Africa (Bond & Templeton, 2011), but not so much in urban areas. The impact of the technology could be considerable, depending on the size of the urban area and the availability of separated organic waste as a feedstock.

2.4. The economics of small-scale biogas operation

The first aspect of economies is that of a large-scale operation compared to a small-scale operation, which naturally requires an economic analysis. There have been many studies which have tried to make or contest the economic case for small-scale biogas. However, this was again largely concerned with rural biogas units or large-scale commercial operations. It has been argued that the advantage of decentralising removes the necessity to transport a waste fraction to a centralised treatment facility (Lijo, *et al.*, 2017), and thereby saving transportation costs and the concomitant carbon emissions. Additionally, other factors have been modelled, to show that the landfill fee, as well as the operational expenses, both play crucial roles in determining the optimal size and location of a proposed biogas unit (Rajendran, *et al.*, 2014) and make a case for small-scale energy generation on site, at least for biogas from OFMSW. However, for large-scale commercial plants, it has been argued that the economies of scale for the centralised plants outweigh the diseconomies of scale for the transport (Skovsgaard & Jacobsen, 2017). On the household level, the focus is somewhat different, in that the technology must show a saving to the household in their cost of primary energy needs, and in this regard, biogas has proven itself (Yasar, *et al.*, 2017) showing a six year return on investment. In fact, there have been attempts to improve the economics by modifying the biogas operation (Renda, *et al.*, 2016) to improve the return on investment.

The second aspect of economics would be that of widespread rollout of small-scale biogas units. It has been mentioned that China, India, Pakistan and Nepal both boast widespread rollout of small-scale biogas units (De Clercq, *et al.*, 2017) with Nepal boasting the highest number of biogas units per capita. In Africa, there have been programmes from Dutch government in Ethiopia via Dutch support, and by the German government in Uganda via German support. These models work by a partial loan and a micro-financing opportunity to install small-scale biogas units in the rural setting meaning that they are not viable without a portion of grant funding. In effect, policies have been put in place for such programmes. In 2015, a group attempted a pilot study on scaling and commercialisation of small-scale biogas units (Sovacool, *et al.*, 2015). The findings confirmed the notion that while the technology had potential, policies were required to support the widespread rollout.

2.5. Factors governing the operation of small-scale biogas

Before reviewing the factors that affect the operation of biogas units, it is imperative to understand the process of biogas production. The production of biogas itself is carried out by four main groups of microbes as depicted in Figure 1, which shows the four main stages in anaerobic digestion (Chynoweth & Isaacson, 1987). The first, hydrolysis, is the breakdown of large polymers into the simple substrates. The second, acidogenesis, carried out by fermentative bacteria, produces volatile fatty acids and some carbon dioxide. These volatile fatty acids are then converted to acetate by a process called acetogenesis. Lastly, methanogenic bacteria produce methane and carbon dioxide from the acetate, hydrogen and carbon dioxide (Grebben, *et al.*, 2008). Each of the main four subsets of microbes operate in their own niche conditions (Cheng, *et al.*, 1987) and each of these microbes have different resilience and activities (Wang, *et al.*, 2004). The microbial population is typically introduced in the start-up phase of operation. Where the feedstock is cow-manure, the microbes will all be naturally occurring. However, if the feedstock is OFMSW, then inoculation (typically with cow manure) will be needed and the population will need to be maintained throughout the operation of the biogas system (Monnet, 2003). If conditions are not favourable, certain populations may die out and re-inoculation will be needed. The inoculation is a biological process, and is the period needed to get to optimal operation, so there have been studies on how to reduce this time (Adl, *et al.*, 2012).

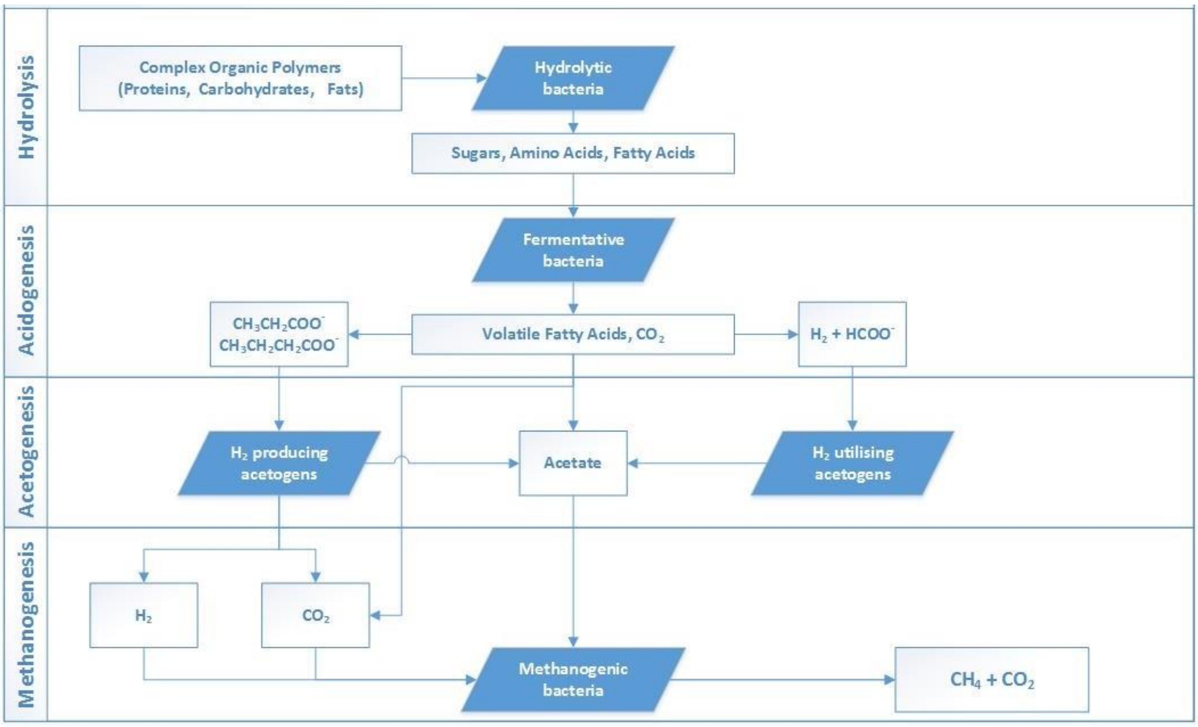


Figure 1. Schematic representation of the anaerobic digestion process (Divya, *et al.*, 2015).

Additionally, the different processes have different optimum pH levels. Acidogenesis occurs optimally at a pH between 5.5 and 6.5, while the optimal range for methanogenesis is between 7.8 and 8.2. In single-stage small-scale biogas units, both microbes will be in the same aqueous environment, and so it is necessary to operate at a pH which suits both populations, usually between 6.8 and 7.4 (Boe & Angelidaki, 2009). Hydrolysis and acidogenesis produce organic acids which inherently lower the pH (Kleinstruer & Poweigha, 1982), and affect the activity of other microbes in the system (Brummeler & Koster, 1989). Most significantly, with regard to the methanogens, if the pH drops too low, microbes become inactive and no methane is produced (Ward, *et al.*, 2008). However, the other three processes will still occur and produce an increased amount of acidity, thereby inhibiting the system. At some point, the methanogens would then die out and the resulting gas produced would be carbon dioxide rich and largely devoid of methane. It therefore matters what the feeding regime would be. Feeding simple sugars allows rapid hydrolysis.

With regard to the composition of feed, much importance has been attributed to the **carbon to nitrogen (C:N) mass ratio** (Cuetos, *et al.*, 2008). This is the amount of carbon over the amount of nitrogen present in the feed by mass ratio (Bernal, *et al.*, 2009). The optimum C:N is 20 - 30 (Gomez, et al., 2006). Although discussed later in Section 2.6, it is worthwhile mentioning that one of the main differences between urban and rural biogas units is the nature of the feedstock. In rural settings, the feedstock is largely **homogenous**, while this is certainly not the case with OFMSW (Resch, *et al.*, 2010). In this regard, the C:N becomes very important when attempting to optimise the performance of a biogas unit (Sisnowski & Wieczorsk, 2003), as there may be high breakdown of feedstock with low methane production, and vice versa (Forster-Cerneiro, *et al.*, 2008). Also, with regard to the feed, the **particle size** would be important, because of the increased surface area to volume ratio with smaller particles (Agwunwamba, 2001).

Practically, for small-scale operations, this may involve mechanical processing of larger particles, and is a notable form of **pre-treatment**. The amount of water, or conversely, the quantity of solids also has an effect on the operation of the biogas unit. Low **total solids** systems range from 1-5% mass fraction of solids, whereas high total solids systems range from 11-15% mass fraction of solids (Kaltwassar, 1980). The amount of **water** and solids naturally influence the **organic loading rate**, which is the rate of organics fed to the system per unit of reactor volume. Furthermore, the amount of water crucially affects the **hydraulic residence time** inside the system. There are therefore optimal organic loading rates which are dependent on temperature, type and quantity of feed (Fang, 2010). In that study, they were noted to be optimum between 0.5 and 0.6 $kg.m^{-3}.day^{-1}$, while other studies which have aimed to reduce acidogenesis have reported acidosis occurring above 3.0 $kg.m^{-3}.day^{-1}$ (Goux *et al.*, 2015). In cases where the aim is to produce volatile fatty acids, the organic loading rate can be increased to 20 to 30 $kg.m^{-3}.day^{-1}$. $kg.m^{-3}.day^{-1}$ (Demirer & Chen, 2004). Crucially, since all the reactions all occur in an aqueous environment, the production of biogas is significantly reduced when there is above 80% mass fraction of solids (Rajeshwari, *et al.*, 2001).

Besides the feeding regime, external factors are also important, and most important, considering that this is a biological process, would be **temperature**. Similar to acidity, each microbe would have an optimum temperature. However, given that in most cases, all microbes would be at the same temperature, the microbes would typically function optimally at either mesophilic or thermophilic temperatures (Igoni, *et al.*, 2008). Below 65 °C there would be a linear relationship, whereby an increase in temperature would increase microbial activity, and therefore biogas production (Karangiannidis & Perkoulidis, 2009). Above 65 °C, the microbial populations would die off and the rate of production would drastically decline. Large-scale biogas units can be tuned to operate in the mesophilic or thermophilic ranges. Mesophilic are the more predominant (Tchobanogolous & Burton, 1981) with many kinetic studies being carried out in that range (Veissmen & Hammer, 1993). Thermophilic operations are generally considered to be more productive but subject to instabilities (Kiely, *et al.*, 1997). Without temperature control, small-scale biogas units would operate at ground temperature (if underground) or ambient temperature (if above ground). This would largely depend on the climate, but is almost always below the mesophilic range of 35 °C to 45 °C.

The **reactor configuration** has also been identified as important. It is known that the productivity is a function of the geometry of the biogas unit (Khanal, 2008). Two-stage digestion, with hydrolysis, acidogenesis and acetogenesis in one stage and then methanogenesis in the next has been shown to improve biogas production in certain cases (Liu, *et al.*, 2006), which in turn improves the economic viability (Renda, *et al.*, 2016). The hydraulic retention time is vital in continuous systems. Production usually increases to a point of “washout”, where the microbes leave the system before they can reproduce (Deublin & Stenhouser, 2008).

It is also known that methanogens, being anaerobic bacteria (Mudrack & Kunst, 1991) may be inhibited by the presence of increased **oxygen** (Hungate, 1996). Biogas systems on the whole are tolerant to limited amounts of oxygen (Morris, 1975). The redox potential can be used as an indication of methanogenesis (Archer & Harris, 1986), where the redox potential for anaerobes is known to be between -200 mV and -400 mV (Hungate, 1967). Oxygen inhibition Is only one of the forms of inhibition. The C:N ratio mentioned previously is significant because a high nitrogen content results in the production of ammonia which is also inhibitory to methanogens. Other inhibitory by-products include **volatile fatty acids** and **sulphide**s (Konzeli-Katsiri & Kartsonas, 1986). Some investigations on the adaptation and resistance of the microbes under acidic conditions and high organic loading rates has been done on the laboratory scale (Goux *et al.*, 2015). These investigations showed that some of the microbes were able to survive the highly acidic conditions and recover from such episodes, returning to normal biogas production after a few days. This may be an indication of resilience or adaption on the part of the microbes.

Thus, it is observed that many detailed studies have been carried out to determine the factors which affect biogas operation. There is a need to isolate those which are most crucial to the operation of small-scale biogas units. It is apparent that the feeding regime appears to play a key role in the operation of the biogas units and is the primary parameter which can be controlled. Based on these learnings, a focus is now taken on urban biogas installations, considering which of the factors might be of most significance.

2.6. Considerations for urban biogas installations

It has been identified in Section 2.3 that there has been extensive roll-out of biogas units in some developing countries (mostly Asia). These apply largely to rural settings, and not urban ones. Before identifying the challenges facing urban biogas units, it is important to understand how they are different from rural ones.

When considering the size of the biogas unit, rural units would be on a household scale (Akinbami, *et al.*, 2001), or an institutional scale (Arthur & Baidoo, 2011). For urban systems, there has been a particularly noteworthy attempt for the rollout of biogas and the twenty one units were installed at institutional levels, e.g. a prison (Barry, *et al.*, 2011). However, if the intended application is the informal sector, there are two major challenges around infrastructure. The first consideration would be where the unit would be installed, and the second would be around ownership of the biogas unit, as well of the gas produced.

It was also mentioned that when considering waste-based biogas, the rural units would typically have a more homogenous feed, by way of animal manure and agricultural waste. Agricultural waste may be seasonal, but still consistent. In rural settings, OFMSW would typically only make up a small fraction of the waste stream (Ghimere, 2013). However, in urban settings, OFMSW would be the main feedstock. Challenges in this regard may arise around the purity of the organic waste, as common practice is not source separation. On the large-scale, urban biogas in an industrial setting could have a homogenous feedstock, e.g. abattoir, brewing, feedlot. However, on the small-scale application, the feedstock would be heterogenous due to the nature of OFMSW.

Considering the outputs from the biogas unit, the first is naturally the biogas. For all small-scale biogas units, the gas is used to meet primary energy needs, which is usually cooking, but has been used for lighting and sometimes heating (Tumwesige, *et al.*, 2014), whereas, on the large-scale, it may be used for power generation and to supplement process-heat requirements to improve efficiencies (Gebreegziabher, *et al.*, 2014). The other output is the digestate. Smith *et al.* (Smith, *et al.*, 2014), in their review, found numerous studies which show the advantages of the nutrient value from composting the digestate. On the whole, in the rural setting, biogas has been shown to improve rural livelihood by meeting primary energy demands and improving soil quality (Smith & Avery, 2014). For urban units, it is normal for large-scale operations to compost the digestate or sell it on to a composting facility which will do the same. However, on the small-scale, and depending on the location, the digestate itself may prove to be a challenge in the urban setting. Furthermore, the inability to valorise the digestate may affect the economic case of the technology.

2.7. Synthesis & Contextualisation

This section will bring together the key points of the review under the headings of “stability”, “productivity”, and “remote monitoring”. Each section will discuss key outcomes from the literature reviewed and how it may be relevant to the objectives of this thesis from Section 1.4. The objectives are re-stated here, now reinforced with relevant literature as follows:

1. Various studies have indicated that the feedstock variability will have an effect on the stability of the biogas system. Given the complex chain of reactions which occur, from acidogenesis through to methanogenesis, and the different rates of these reactions, the feeding regime (including possible pre-treatment) is likely to be a key factor in the stability of the system as a whole, particularly on the small-scale. Quantifying and qualifying the effect would prove useful in the successful operation of small-scale biogas units.
2. Since biogas units are biological systems, operating temperature would affect the biogas yield. As per point 1, understanding and qualifying this effect would prove useful in the successful operation of small-scale biogas units.
3. Lastly, since biogas is a complex technology requiring some expertise to operate successfully, there would be a necessity for knowledge support for successful operation and to safeguard investment.

2.7.1. Small-scale biogas in Africa and the role of monitoring

Addressing the first and second objectives, there needs to be a definition of the system, and then a definition of productivity and stability. The system may be defined as the whole biogas unit, from the feed inlet, and including the end-user device. Productivity can be defined as the amount of biogas produced per unit mass of feed (if necessary, normalised to reactor volume). The stability of the system is defined as the sensitivity of the system to changes in operation.

Many parameters have been identified which affect the operation of the biogas units, and thereby the productivity and stability of the operations. Furthermore, many of the parameters are linked, and dynamically inter-dependant. The inter-dependency is important because it allows certain parameters to be measured and even inferred from others. For example, volatile fatty acid concentration and pH, where the volatile fatty acid concentration (a typically technology intensive measurement) can be inferred from the pH (a typically low-tech measurement) (Lahav, *et al.*, 2002). The pH would primarily be influenced by the feeding regime. This would be the same case for C:N ratio (which impacts inhibition), the hydraulic residence time (which may influence washout) and the particle size (which would affect productivity). The feeding regime therefore appears to be of paramount importance when considering operational success. Furthermore, pH can be monitored as a linked parameter as an indication of operational stability. Another low-tech measurement is flame quality, in the instances noted above where there would be high acidity and therefore production of carbon dioxide over methane, the flame would burn yellow as opposed to blue. Monitoring of parameters to ensure productivity and stability may be crucial in itself to safeguard investment.

The design of the unit, and the context of its installation may also govern the success of the unit. There are different designs, but more complex often means more expensive, which works against affordability in the context of energisation. Lastly, although it is recognised that anaerobic digestion is a biological process, there is no control over the actual microbes responsible for the process, apart from the initial inoculation. That being said, it is observed that the microbes are sensitive to temperature. Again, for simple systems, there would not be any temperature control, so this would largely be a function of the climate of the location where the biogas unit is installed.

2.7.2. Operational challenges in the urban setting

Having understood the differences between urban and rural systems, the challenges which may face urban biogas rollout can be considered from the angle of feasibility. The economics of small- versus large- scale has already been debated in Section 2.4, so in this section, the discussions will only be relevant to *small-scale urban* biogas units.

In addition to the operational concerns around productivity and stability, it appears that there may be two more concerns when dealing with small-scale urban biogas units. Section 2.7.1. draws attention to the fact that feeding regime has a significant effect on the operational stability and that the nature of the intended feedstock (OFMSW) is heterogenous, this may prove to be a significant challenge to urban biogas units. Stability and productivity of the system may be further impacted by inconsistencies in feedstock.

While the digestate is seen as a valuable by-product in rural cases, the digestate, without a use, in the urban setting may prove to be a challenge. It may also detract from the feasibility of small-scale urban biogas units as a whole.

2.8. Summary

The success of small-scale operations will depend largely on the ability to maintain stability and high productivity of these units and may beg the need for monitoring and control of important parameters in a cost-effective manner. The technology itself comes with operational concerns, which themselves are exacerbated in small-scale units, where small reaction volumes are more susceptible to minor perturbations. The feeding regime has been identified as critical for reliable production of biogas, which may necessitate monitoring (and in indeed smart-monitoring when considering widespread rollout) to safeguard investments.

There has been widespread rollout in Europe and Asia which have preceded some European initiatives in some African countries to promote small-scale biogas units in rural settings. However, apart from a few institutional units, there have not been any attempts to promote small-scale biogas in the urban setting. The urban setting itself brings with it its own set of challenges. The two main challenges identified are the heterogeneity of OFMSW which may impact operational stability of the biogas unit, and the effective use of the nutrient rich digestate. The use of the digestate also has an economic impact, as the nutrients have value and impact on the financial case for the technology.

These concepts are central to the potential success and understanding the limitations of small-scale biogas in urban Africa.

Chapter 3: Methodology

Based on the literature reviewed, the problem statement from Section 1.3 is now built upon. The problem statement outlined that access to energy services had been identified to play a pivotal role in sustainable urban development, particularly in the fast-developing cities of the global south. Now, based on the literature reviewed, it is apparent that decentralised, small-scale biogas units characterise a technological intervention that would potentially fit well into this context as a solution to energy demands, with additional waste management and sanitation benefits. Although the technology has been well researched, with a large scientific body of literature (making it principally ready to deploy), there is a dearth of application in urban Africa. There is a need to understand the important parameters which would control the productivity and stability of small-scale systems particularly in urban Africa (given that the intended feedstock would be the organic fraction of municipal solid waste), and to identify the support infrastructure needed to maintain the successful operation of such installations.

4.1. Hypotheses

There are three hypotheses which have been formulated through the analysis of relevant literature. These are as follows:

Hypothesis 1: Feedstock variability is a key factor affecting the stability of small-scale biogas units; it is further hypothesised that pre-treatment of the organic waste can improve stability of biogas units.

Anaerobic digestion is a staged process, the first of which is a hydrolysis phase which can occur very quickly with simple carbohydrates and can lower the pH of the system, adversely affecting the balance of biological agents. In small-scale systems, such perturbations would be more significant. Pre-treatment of the organic waste may produce a more homogenous feedstock and therefore improve the stability of small-scale anaerobic digesters.

Hypothesis 2: Ambient temperature is the other determining factor of productivity of small-scale anaerobic digesters to the point that it significantly affects biogas yield of installed digesters across seasons and across locations.

Biochemical reactions increase with temperature as they are based on microbial activity. It is widely accepted that the microbial activity is a function of temperature up to a point where the microbes die when the temperature is too high. Thus, the biogas yield should be higher in warmer climates.

Hypothesis 3: Smart monitoring of key parameters will improve stability and thus productivity of small-scale biogas units.

Given the complex nature of the technology, smart monitoring would be needed to provide knowledge support, to safeguard the success of the technology if it were indeed to be adopted in a widespread rollout.

4.2. Approach

To gather evidence in support of the hypotheses, the proposed approach was, of necessity, located more in the field than in the laboratory. The framework of the investigations undertaken were formulated around opportunities and projects which arose organically over the development of the research project. Overall, the application of research undertook the following phases:

- **Phase 1:** Initial Field Observation. This was the study of one particular unit, to understand factors which affected productivity and stability in a controlled environment. This unit was also used to test and hone the remote monitoring parameters and methodology for the next phase.
- **Phase 2:** Remote Monitoring. This was the widespread application of the parameter monitoring procedure informed by Phase 1 presenting a large amount of data for analysis of key trends and providing insights to test hypotheses.
- **Phase 3:** Field Experimentation. This was taking some of the learnings from Phases 1 & 2 to set up experiments in another controlled environment.

These steps are summarised in Figure 2, which also illustrates how the different studies related to each other under the broader thesis objectives - whereby the initial field observation tested and informed the remote monitoring study to be undertaken. Similarly, analysis of the data from the remote monitoring study led to the formulation of test work undertaken in the field experimentation.

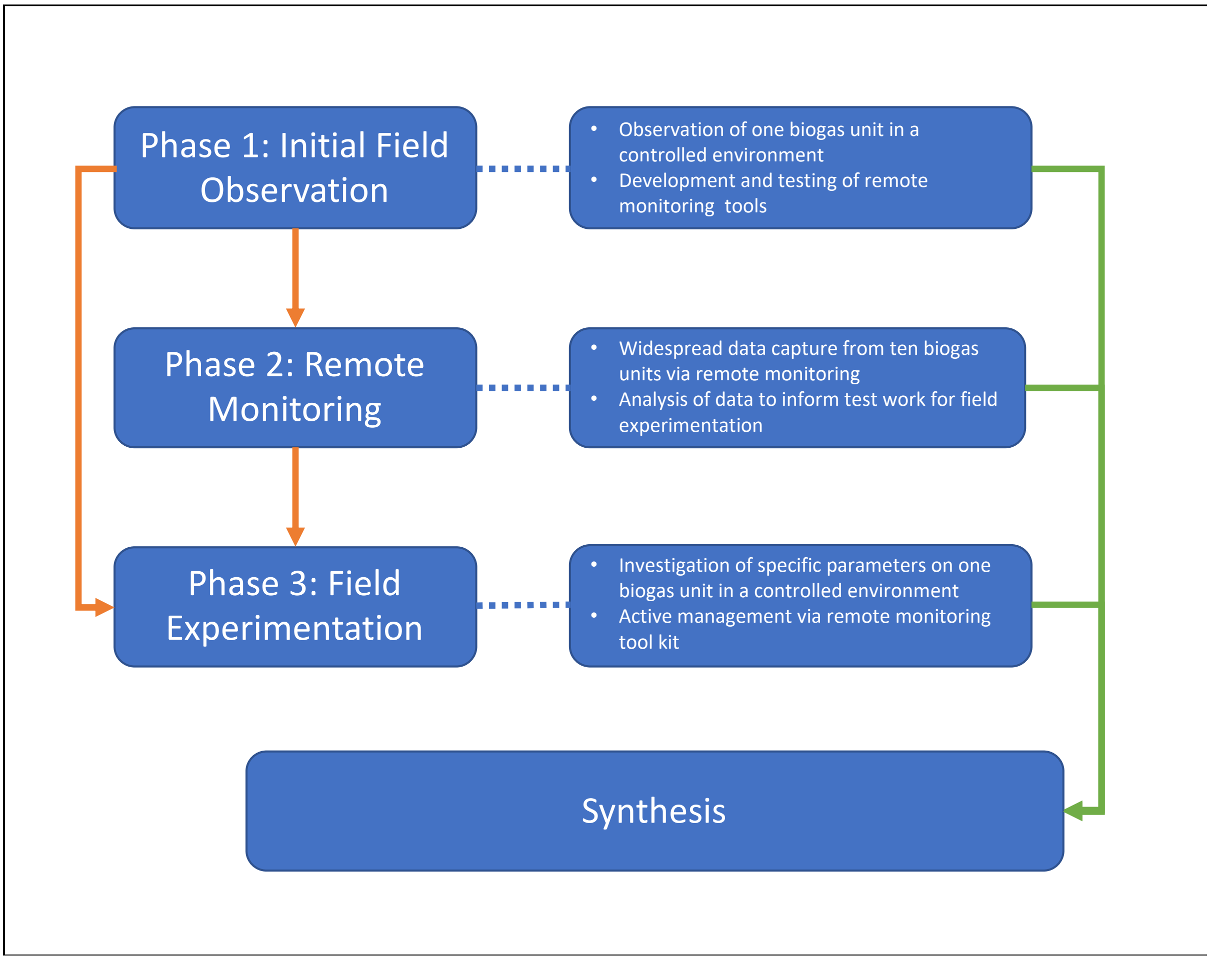


Figure 2. Schematic summary of the approach taken in Phases 1, 2 and 3 with a description of each phase (- -) and their interrelation (–) as well as the information flow (–) to address the objectives.

With respect to the actual units chosen, in some cases, the Environmental & Process Systems Engineering (E&PSE) research group at UCT was a stakeholder in some of the chosen studies, and in others, willing collaborators were used. These projects are summarised (at their status quo in 2011) in Appendix F. For example, there was a biogas unit which was to be commissioned at a UCT student residence through a project funded by the Vice Chancellors' Strategic Fund (Appendix F1). This presented an ideal test unit to undertake a set of investigations for the initial field observation to start addressing Hypotheses 1 & 2. The unit was also used for the development of the remote monitoring methodology, identifying which parameters could be monitored and then trial analytical methods. This culminated in a smart phone application and monitoring toolkit, the methodology for which is further discussed later in Section 4.2.2.

For Phase 2, the manufacturer/supplier of the initial unit was able to provide contact details of other small-scale biogas units in the region, all of whom were contacted to find some willing collaborators to use the now-built mobile phone application. Once the monitoring methodology was finalised, the application was rolled out and sent to ten test units across southern Africa over 2012 and 2013. The biogas unit at the university residence was one of the units in the monitoring study, and as some contacts were sourced through the supplier four other biogas units were the same model as the biogas unit in Phase 1, allowing for comparisons. The aim was to generate a wealth of data from biogas units in urban settings with different feedstocks and in different climates to further address Hypotheses 1 & 2 respectively. Furthermore, there existed a smart monitoring service as this data was being collected via smart phone application. There was also a level of interaction and support with the biogas operators.

In 2014, an opportunity arose to undertake further investigations on another biogas unit with the owner wanting to prove the case of using the organic fraction of municipal solid waste as the sole feedstock for an urban biogas unit. Based on learnings and experiences from Phase 2, key parameters were chosen to carry out a tailored investigation on this unit which became Phase 3, starting in 2014. The pre-treatment of feedstock as well as staggered introduction of simple carbohydrate feed was investigated to specifically speak to Hypothesis 1, while the now standardised remote monitoring from Phase 2 was used to further speak towards Hypothesis 2.

All three phases of research involved remote monitoring. Phase 1 involved the development of the monitoring methodology. Phase 2 used the tool to gather data and interact with some of the users. Phase 3 actively used the tool to manage a biogas unit remotely. Thus, all three phases provided learnings which addressed Hypothesis 3.

4.2.1. Biogas units monitored

As mentioned in the previous section, there were three distinct phases to the research. Phase 1, which occurred over 2011 and 2012, utilised the biogas unit at the university residence. As it was the first unit and at UCT, it was termed the UCT biogas unit. This unit was also included as one of the units in the monitoring study - Phase 2, which took place over 2012 and 2013. Phase 3 came a full year after Phase 2, only starting in May 2014 and utilised a biogas unit at a local composting facility and was hence termed the LCF (Local Composting Facility) unit.

The comparisons between the two units in controlled environments, namely the UCT and LCF biogas units are shown in Table 1, while the profiles of the biogas units used in the remote monitoring study are shown in Table 2.The UCT biogas unit, presented in Table 1 is in fact also the first unit, (Unit 1) in Table 2.

Table 1. Comparison between the University of Cape Town (UCT) and Local Composting Facility (LCF) Biogas Units used in Phases 1 and 3 respectively.

	UCT Biogas Unit	**LCF Biogas Unit**
Feed	OFMSW from canteen	OFMSW from a mall
Pre-treatment	None	Grinding Sometimes Bokashi
Gas Use	4.5 kW stove – canteen	4.5 kW stove – outhouse
Digestate outlet	Sewer	Tank storage then compost

In Phase 2, the biogas units differ in location, size, feeding regime and the rating of the stoves used. With respect to feedstocks, [O] = OFMSW, [S] = Sewage, [M] = Manure, [A] = Agricultural Waste. Where the units were fed with sewage the typical household occupancy was noted for calculation purposes. Units 2, 6 and 9 were at an urban garden, a guesthouse and another urban garden respectively. Unit 1 was at a university and Unit 10 was at a school. These are referred to as an institutional unit [I]. The institutional units all had large biogas stoves with a power rating of 4.5 kW. The remaining five units, namely; 3, 4, 5, 7 and 8 were all at domestic units [D], which all had smaller biogas stoves, with a power rating of 2.8 kW.

In order to easily identify each digester and what its properties were, each one was referred to by its full descriptor as follows: number.(location).size.[feedstock1][feedstock2].[type]. For example, Unit 4 is referred to as 4.(EC).6.[O][S].[D]; being Unit 4, in the Eastern Cape (EC), having a size of 6 m^3, fed with Organic Waste [O] and Sewage [S], and being a domestic installation [D] - the last descriptor also indicating that it has a 2.8 kW stove.

Table 2. Description of the properties of biogas units monitored in Phase 2.

Unit	Location	Size (m^3)	Feed	Type	Stove rating (kW)	Occupancy
1	Cape Town (WC)	6	[O]	[I]	4.5	-
2	Worcester (WC)	10	[O]	[I]	4.5	-
3	Cape Town (WC)	6	[O][S]	[D]	2.8	2 to 3
4	Grahamstown (EC)	6	[O][S]	[D]	2.8	3
5	Swaziland (SWZ)	6	[O][S]	[D]	2.8	4
6	Kleinmond (WC)	20	[O][S]	[I]	4.5	9
7	Limpopo (LIM)	8	[A][M]	[D]	2.8	-
8	Durban (KZN)	8	[A][M]	[D]	2.8	-
9	Cape Town (WC)	10	[A][M]	[I]	4.5	-
10	Cape Town (WC)	6	[M][S]	[I]	4.5	5

Key:		
	[O]	Organic Fraction of Municipal Solid Waste
	[S]	Sewage
	[A]	Agricultural Waste
	[M]	Manure
	[I]	Institutional
	[D]	Domestic

The stoves themselves were supplied with the biogas unit when installed. A summary of the properties of the stoves in presented in Table 3. The manufacturer in both cases was Shenzhen Puxin Technology Co. Ltd (Puxin, 2019), a large Chinese manufacturer, which is a renowned supplier of biogas components. The stove properties were taken from the manufacturer. A calculation was done to confirm that the gas flow rate correlated with the stove rating. The smaller biogas stove used in the domestic installation was confirmed to have a power rating of 2.8 kW with a gas flow rate of 0.45 $m^3.hr^{-1}$. However, using the same calculation methodology, a gas flow rate of 2.5 $m^3.hr^{-1}$ (which is the rating from the manufacturer) would convert to a stove rating of 15.6 kW. It is known that the stove rating of 4.5 kW is accurate from previous work (Naik *et al.*, 2012). Therefore, using the stove rating to calculate the gas flow rate required to power a 4.5 kW, a gas flow rate of 0.72 $m^3.hr-^1$ is the calculated factor. This calculation methodology is presented in Section 4.4.1, while stove properties are listed below.

Table 3. Properties of biogas stoves used in the study (Puxin, 2019).

	Large Stove [I]	**Small Stove [D]**
Gas	Biogas Only	Biogas/LPG
Power Rating (kW)	4.5	2.8
Gas Usage ($m^3.hr^{-1}$)	0.72[1]	0.45
Heat Efficiency	>57%	>57%
Gas Entrance Pressure (kPa)	1.6	1.6
Fire maker Efficiency	>98%	>98%

There was one other biogas unit which formed a small part of the monitoring. In November 2018, which was between the original submission (March 2017) and this re-submission (in June 2019), a unit was installed at N1 City Shopping Mall in Cape Town (Waste Transformers, 2018). It was monitored remotely from the Netherlands who gave instruction to operational staff at the shopping mall. This unit was only used in an investigation on the accuracy of using pH test strips, as described in Sections 4.2.3.1 and 4.2.1. Since it was not part of the core study, it was not included in the main group of biogas units used in the study.

---

[1] Calculated

4.2.2. Development of the mobile phone application for remote monitoring

In early 2012, a smartphone application was developed to assist with the remote capture of data. The application which was inspired by the Aquatest App (Appendix F3) and consisted of two components. The first component was a digital form, completed by the user, by filling out sections in various fields when prompted. The second component was a photo assessment, whereby a photo of a water-quality sampling test-kit would be evaluated by software and a reading returned. The logic for the first component was adopted for the biogas monitoring toolkit, initially using the digital form completed by the users in remote location and submitted to a central database. The second component, i.e. the photo application was to be a future development if necessary. The form itself was coded into a JAVA application and loaded onto a Nokia C2-00. The development of the application was commissioned to the Spatial Data Research Group in the Department of Civil Engineering at UCT. This is the research group which built the Aquatest App (UCTCivEng, 2011) and deployed it in the same way (onto Nokia C2-00 smartphones to be used in the field). The welcome screen for the mobile phone application is shown below in Figure 3.

Figure 3. Picture of the welcome "splash" screen for the Biogas Monitoring Tool application used for the remote monitoring study from Phase 2 onwards.

The parameters recorded in the digital form are shown in Table 4, along with how the parameter was measured, and the type of field that the user would have to input data.

Table 4. Parameters reported through the Biogas Monitoring Tool application in Phase 2.

Parameter	Method of measure	Input by user
Date	From phone	None
Mass of feed	Weighed or estimated	Number input only
Description of feed	Observation	Free text
Volume of water added	Weighed or estimated	Number input only
pH	Indicator strip	Number input only
Pressure	Recorded from in-line pressure gauge	Number input only
Burning time	Estimated	Number input only
Flame quality	Chosen from list as follows: • Stable blue • Yellowish • Unstable	Selection
Sample taken (of digestate)	Chosen from list as follows: • Yes • No	Selection
Username	-	Free text
Temperature	From weather report	None

Some screenshots of the user interface as depicted through an emulator are shown in

Figure 4. The figure illustrates what the interface screen would look like on a Nokia C2-00 mobile phone. A photo assessment feature which was part of the Aquatest App was not deemed necessary for the Biogas Monitoring Tool in this study and so was earmarked as a potential future development.

Site Name	Area
100I AD1	UCT
100I AD2	UCT
Leo Marquard Hall	UCT

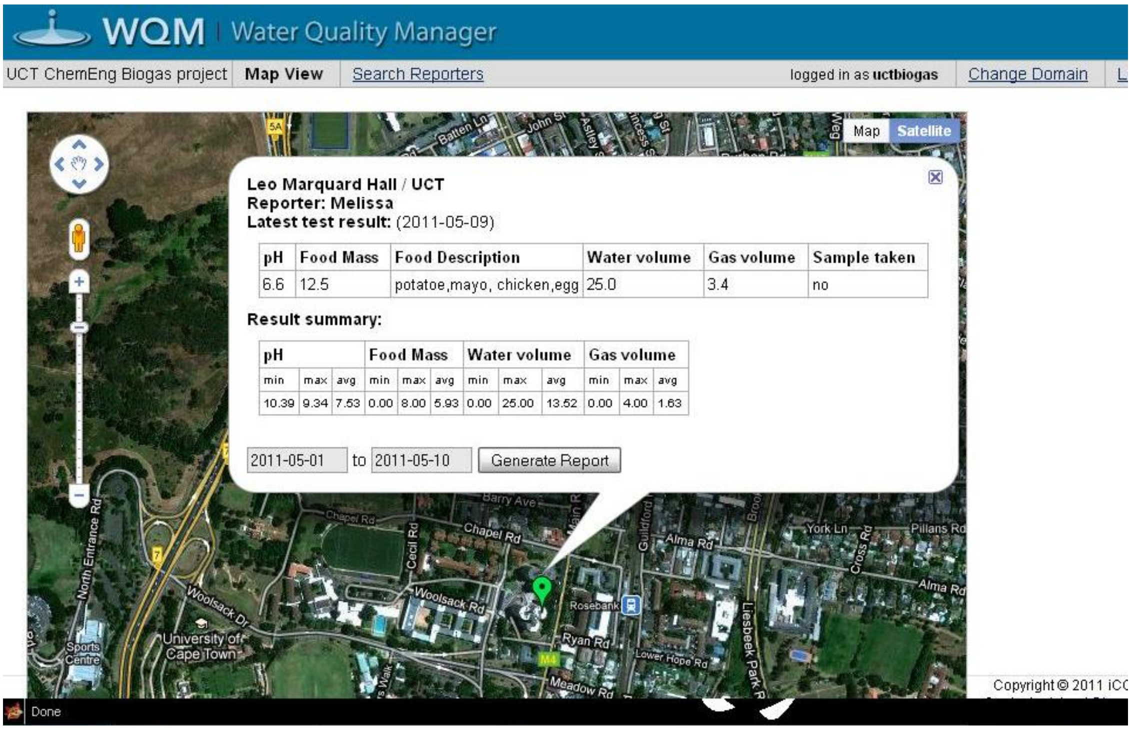
*Mass of food waste added (kg)
7

Site code: AD1UCT1
Site name: 100I AD1
Area: UCT
Assessment date: 09/05/11
Time:
Mass of food waste added (kg): 7.0
Description of food waste:
Volume of water added (litres): 10.0
Current pH: 12.0
produced: 2.0
been taken?: yes
inus

Figure 4. Screen from the user interface of the Biogas Monitoring Tool application as displayed on an emulator for a Nokia C2-00.

Once completed, the form was saved and sent to a centralised database on a server via mobile network for the data to be retrieved online.

In mid 2012, the user interface for the Aquatest App was integrated with Google Maps so that the data which was captured could be retrieved through a Google Maps interface as shown in Figure 5. This feature was naturally extended to the Biogas Monitoring Tool data on the same interface. Furthermore, a report could be generated for a specific time period and exported to MS Excel. A note here that the pin, which is currently green in Figure 5, was later coded so that it would turn red when the most recent pH reading was below 6.0.



Leo Marquard Hall / UCT
Reporter: Melissa
Latest test result: (2011-05-09)

pH	Food Mass	Food Description	Water volume	Gas volume	Sample taken
6.6	12.5	potatoe,mayo, chicken,egg	25.0	3.4	no

Result summary:

pH			Food Mass			Water volume			Gas volume		
min	max	avg	min	max	avg	min	max	avg	min	max	avg
10.39	9.34	7.53	0.00	8.00	5.93	0.00	25.00	13.52	0.00	4.00	1.63

2011-05-01 to 2011-05-10 Generate Report

Figure 5. Illustration of the User Interface of captured data for a monitored site.

The Biogas Monitoring Tool application became integral in gathering data in Phases 2 and 3. It was simply loaded onto several Nokia C2-00 mobile phones and formed part of the monitoring methodology as described in Section 4.3 below. Also, as it was on a mobile phone, that phone itself was used a means of communication with the biogas operators, particularly when there was an incidence of low pH which could now be easily observed from Figure 5.

4.2.3. Measurement of specific parameters

Specific parameters which were considered to be important in evaluating the productivity and stability of biogas units were monitored, sometimes in more than one way. For acidity and temperature, laboratory level equipment (such as probes) were used in Phase 1, while more simple methods which would be easier to measure (even though the result may be more less precise measurements) were adopted in Phase 2. A description of the monitoring methods is presented in this section.

4.2.3.1. Measurement of pH

With regard to the monitoring of the pH, there were two different methods implemented. In most of Phase 1, a portable pH probe was used - a laboratory level Crison 25+/148019 portable probe, which was calibrated in the lab with 4.00 and 10.00 calibration buffers before taking each pH reading.

For the last part of Phase 1 and all of Phases 2 and 3, an indicator strip chosen was used. The strip is shown in

Figure 6. While there are many types of indicator strip available, the advantages of the one chosen were threefold and outlined as follows:

- Locally available to order online, which meant that indicator strip could be sent to remote monitoring locations easily.
- The indicator paper was easy to use. There was only one colour to match to the kit to discern the pH (other test kits often have 4 to 6 squares to read results from to ascertain pH).
- The optimal pH range for a biogas unit has been identified as 6.8 to 7.4 with a broader optimal range identified as 6.0 – 8.0. In that range, this pH indicator is green, so it can be inferred to a user that: “Green = Healthy”.

Figure 6. pH indicator strip used to measure pH of biogas digesters (Distillique, 2016).

Comparison of the different sampling methods for pH was done in three different studies. Firstly, for a period during Phase 1, both the pH probe and the indicator strip were used to take readings at the same time to evaluate the suitability of using the indicator strip. Secondly, Unit 4 in Phase 2 was operated by a user who had access to a calibrated pH probe, so there was additional comparative data available from that unit. Thirdly, the unit installed at N1 City Shopping Mall mentioned in Section 4.2.1. was monitored remotely from the Netherlands, including the parameters of temperature and pH. Therefore, it was possible to take readings with the indicator strip and compare them to the recorded data with the pH probe. This comparison is presented in Chapter 4.

4.2.3.2. Measurement of temperature

Temperature monitoring was also carried out in two ways. The first (for the greater part of Phase 1) was using a temperature probe, the same Crison 25+/148019 probe which measured pH to obtain the temperature inside the unit. The second was by referring to online weather reports (AccuWeather, 2012) and recording ambient temperature. Comparisons between these two methods are also presented in Chapter 4.

4.2.3.3. Weighing of feedstock

The mass of food was weighed by picking up a bucket (which had previously been weighed to tare) with an analogue hanging scale. The tare weight was then subtracted from the weight of the bucket mentally and the resulting weight recorded. Where water was added, the volume of the bucket was used to estimate the volume and recorded in the relevant field on the digital form.

4.2.3.4. Observation of pressure

Most biogas units (certainly all the ones in this study) were installed with a pressure gauge. In some cases, as in the initial field observational study, the pressure gauge reading was recorded as a cross check for the gas utilisation. If gas was utilised, the pressure reading should be lower. Thus, the decrease in pressure over a period of gas use, i.e. recording the pressure before and after cooking would be the only way of recording meaningful data. A daily reading of pressure would not be useful as gas was continuously produced. A study which recorded the decrease in pressure over a period of cooking was carried out over ten weeks in Phase 1 – the initial field observation. The actual recording of the pressure through the digital form was later excluded as a measurement parameter in the monitoring study for the reason that there was typically only one daily recording from users and this parameter was no longer deemed useful to measure.

4.2.3.5. Recording of ‘burning time’

Time of flame burning, or the “burning time” was estimated to the nearest five minutes by the user and recorded as a field in the Biogas Monitoring Tool application data form.

4.3. Operation, monitoring and measurement methodology

The monitoring in Phase 1 was hands-on and was therefore the most intensive of all three phases. It not only informed the monitoring methodology for Phase 2, but also justified the use of the certain measuring techniques. In Phases 2 and 3, the monitoring methodology via the phone application was already well established. Phase 3 was a planned experimentation on a unit with active input and management of the feeding regime as described below.

4.3.1. Operation and monitoring in Phase 1

A 6 m^3 biogas unit was commissioned in a controlled environment at a university residence – UCT biogas unit. The unit was inoculated with cow manure and then fed varying amounts and types of OFMSW from a residence canteen. The project was divided into four distinct periods. The breaks between the periods were typically demarcated by the university calendar where the kitchen was closed over the June and December vacations and measuring was also not performed over the September mid-semester break. There were sometimes changes in the systems and techniques put in place for monitoring parameters over the thirteen months and these are summarized in Table 5.

Table 5. Summary of changes in monitoring techniques of the parameters measured at the UCT biogas unit between March 2011 and April 2012.

Period	Time	pH	Temperature	Burning Times
1	2011: Apr – Jun	Yes, probe	From Jun, probe	No
2	2011: Aug – Sep	Yes, probe	Yes, probe	Yes, manually
3	2011: Oct – Dec	Yes, probe	Yes, probe	Yes, manually
4	2012: Feb - Apr	Yes, test strip	Yes, weather site	Yes, via App

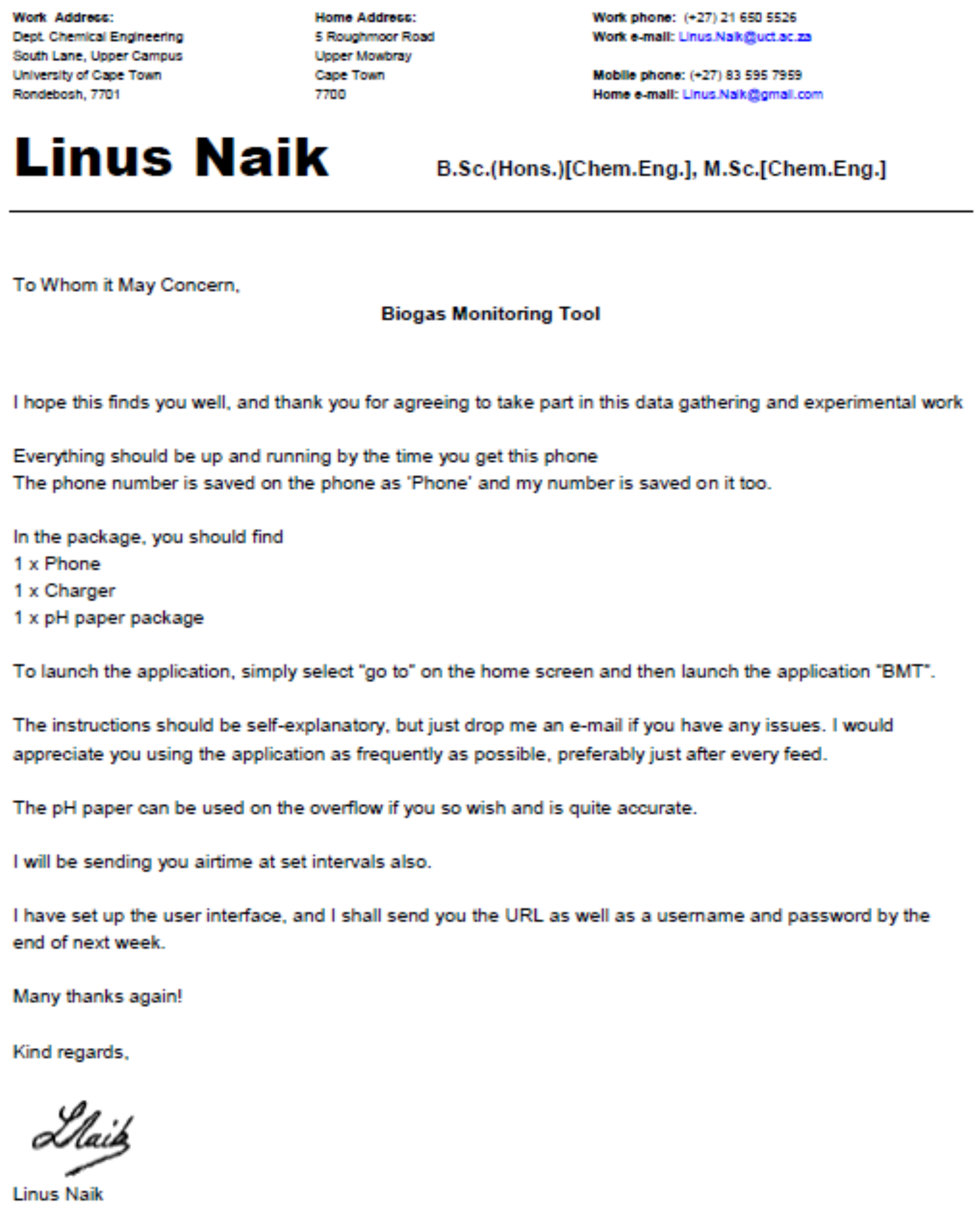
Of note is Period 4, where the pH and temperature probe monitoring were replaced with indicator strip and data from weather sites respectively. The appropriateness of the replacement is discussed in Section **Error! Reference source not found.**. The pH was monitored as an indication of health and stability of the biogas unit. While the unit was still under the operation of the E&PSE Research Group, the pH was measured with the portable pH probe and sometimes cross checked with universal indicator strips. Lime was kept on site and added if pH adjustment was needed. In 2012, when the unit was formally handed over to the student residence, measurements were taken with the indicator strips only. The actual length of cooking referred to as ‘burning times’ were recorded separately over two of the periods. The first instance of this was manually over Period 2, and it then became standard to report this in Period 3, and via the mobile phone application in Period 4.

4.3.2. Operation and monitoring in Phase 2

The smartphone application described in Section 4.2.2 was loaded onto a compatible phone and sent to ten willing operators of biogas units (as described in 4.2.1) around southern Africa - nine of which were in South Africa and one of which was in Swaziland. Figure 7 shows the map of the locations of these biogas units.

Figure 7. Location map of the biogas units monitored across southern Africa for Phase 2.

Initially, the operators were contacted via e-mail, asked for their willingness to be part of the study. If they confirmed their willingness, contact was established telephonically and a letter was sent to the biogas operator along with the mobile phone and the pH test strip, shown in Figure 8. The letter indicated the contents of the package, as well as notes that the airtime on the unit would be topped up at set intervals, along with relevant contact details.



Work Address:
Dept. Chemical Engineering
South Lane, Upper Campus
University of Cape Town
Rondebosh, 7701

Home Address:
5 Roughmoor Road
Upper Mowbray
Cape Town
7700

Work phone: (+27) 21 650 5526
Work e-mail: Linus.Naik@uct.ac.za

Mobile phone: (+27) 83 595 7959
Home e-mail: Linus.Naik@gmail.com

Linus Naik B.Sc.(Hons.)[Chem.Eng.], M.Sc.[Chem.Eng.]

To Whom it May Concern,

Biogas Monitoring Tool

I hope this finds you well, and thank you for agreeing to take part in this data gathering and experimental work

Everything should be up and running by the time you get this phone
The phone number is saved on the phone as 'Phone' and my number is saved on it too.

In the package, you should find
1 x Phone
1 x Charger
1 x pH paper package

To launch the application, simply select "go to" on the home screen and then launch the application "BMT".

The instructions should be self-explanatory, but just drop me an e-mail if you have any issues. I would appreciate you using the application as frequently as possible, preferably just after every feed.

The pH paper can be used on the overflow if you so wish and is quite accurate.

I will be sending you airtime at set intervals also.

I have set up the user interface, and I shall send you the URL as well as a username and password by the end of next week.

Many thanks again!

Kind regards,

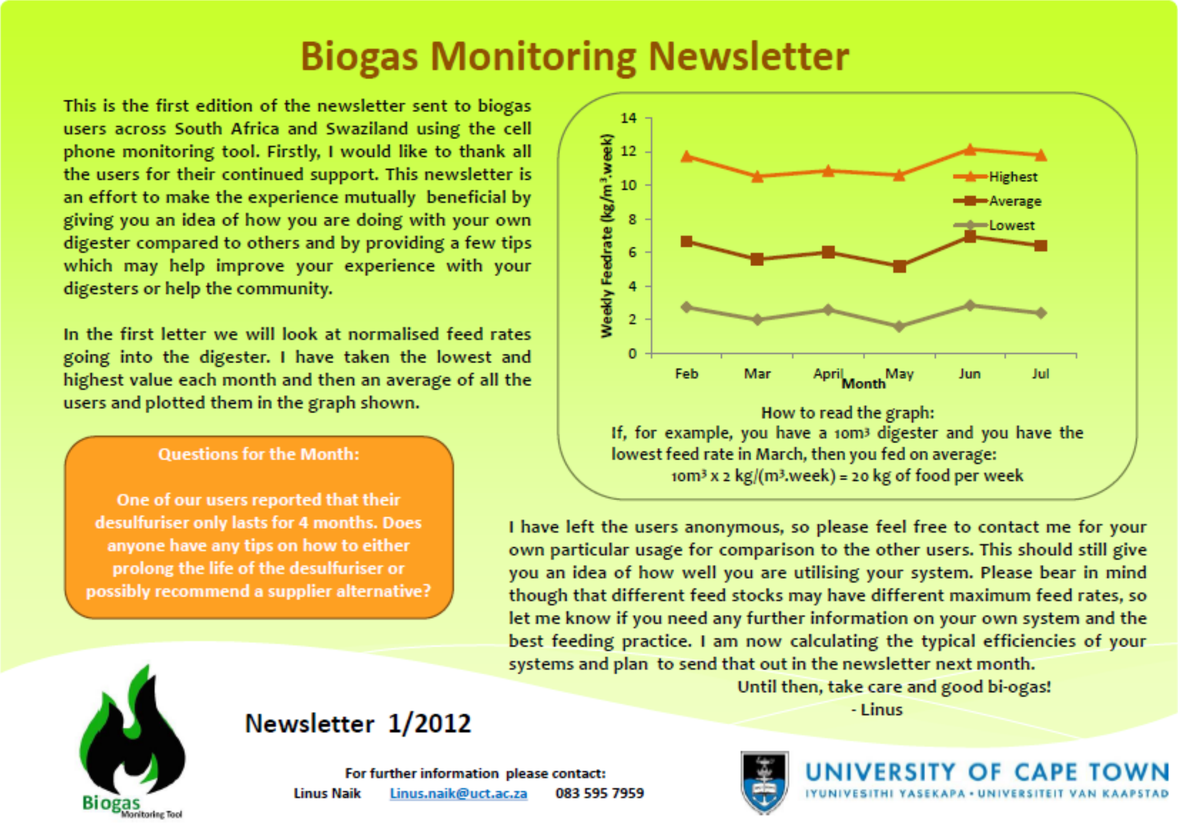
LNaik

Linus Naik

Figure 8. Letter sent to biogas operators at the onset of Phase 2.

Monitoring started in February 2012 with two units (the first being the UCT biogas unit) and the others coming online over the year. The parameters which were observed and reported have been outlined previously in Table 4. These data points were exported to MS Excel for analysis. The operators were interacted with further via a monthly newsletter, an example of which is shown below in

Figure 9. Operators were also contacted by voice call to check on any operational issues, particularly when there was a low pH reading, which was noted by a red pin, at their location as in Figure 7.



Biogas Monitoring Newsletter

This is the first edition of the newsletter sent to biogas users across South Africa and Swaziland using the cell phone monitoring tool. Firstly, I would like to thank all the users for their continued support. This newsletter is an effort to make the experience mutually beneficial by giving you an idea of how you are doing with your own digester compared to others and by providing a few tips which may help improve your experience with your digesters or help the community.

In the first letter we will look at normalised feed rates going into the digester. I have taken the lowest and highest value each month and then an average of all the users and plotted them in the graph shown.

How to read the graph:
If, for example, you have a 10m³ digester and you have the lowest feed rate in March, then you fed on average:
10m³ x 2 kg/(m³.week) = 20 kg of food per week

Questions for the Month:

One of our users reported that their desulfuriser only lasts for 4 months. Does anyone have any tips on how to either prolong the life of the desulfuriser or possibly recommend a supplier alternative?

I have left the users anonymous, so please feel free to contact me for your own particular usage for comparison to the other users. This should still give you an idea of how well you are utilising your system. Please bear in mind though that different feed stocks may have different maximum feed rates, so let me know if you need any further information on your own system and the best feeding practice. I am now calculating the typical efficiencies of your systems and plan to send that out in the newsletter next month.

Until then, take care and good bi-ogas!
- Linus

Newsletter 1/2012

For further information please contact:
Linus Naik Linus.naik@uct.ac.za 083 595 7959

Figure 9. Example of the monthly newsletter distributed to operators in the Biogas Monitoring Tool study in Phase 2.

There is a note here that not all unit were operational for the entire 12 months. Data collected over the periods whenever possible and new users brought onto the system were added to the community.

4.3.3. Operation and monitoring in Phase 3

After the completion of the remote monitoring work, an opportunity arose in 2014 to perform a series of experiments with a biogas unit at a local composting facility to demonstrate the operation of the unit on food waste from a mall. The LCF biogas unit was the same brand of 6 m^3 pre-fabricated biogas unit used as the UCT biogas unit. The digester, with a design capacity of 35 kg per day of organic food waste, was initially inoculated with cow manure and operated on manure for 3 months before being fed with the organic waste from a mall with the digestate being used in the composting operation. There was exclusive access to this unit for the experimental work undertaken.

Compared to Phase 1 and the measurement regime in Table 5, measurements for the LCF biogas unit were recorded as frequently as possible (almost every day) and sent via the same smartphone application, as outlined in Section 4.2.2. In addition, lime was kept on site as it was for the UCT biogas unit, in case pH adjustment was needed.

Table 6. Parameters monitored via Biogas Monitoring Tool application for the LCF biogas unit in Phase 3.

Parameter	Method	Frequency
pH	Indicator strip	Daily
Weight of feed	Scale	Daily
Burning Time	Reported from observation	Daily
Pressure Gauge	In-line gauge visual reading	Infrequently
Ambient temperature	Weather records	Weekly

Unlike Phase 2, readings were checked daily and there was active management (albeit remote) of the feeding regime and instruction sent to the operator. In this way, there was active involvement with the unit operator on an almost daily basis (not just when there was a problem). With regard to the burning time, the gas stove was burned until there was no more biogas left. From here, the burning time was recorded to the nearest five minutes and recorded in the application.

4.3.3.1. Migration to OFMSW

Based on findings from Phase 2, testing on purposive disruptions and stepwise increase of simple carbohydrates was undertaken, along with another investigation on pre-treatment with Bokashi treated waste. As mentioned, the unit was initially primed with cow manure and run solely on cow manure for 3 months (April to June 2014). The biogas unit was first brought to operation on food waste by the stepwise addition of food waste.

OFMSW was fed in fixed incremental amounts of 2 kg every second day, until the weight fed every second day was 20 kg. From thereon, 10 kg was fed daily and increased stepwise until it was operating at 35 kg per day by 1 October 2014. This process took 3 months from 1 July 2014 and the food waste was supplemented by cow manure. At this stage, the contents of one 120 dm^3 wheelie bin (weight varying between 10 kg and 65 kg) was processed through the food waste disposal unit and fed into the unit. The weight of each bin was recorded. When simple carbohydrates were needed, the staff at the mall were instructed to only keep aside simple carbohydrates which were then delivered to the local composting facility.

4.3.3.2. Experimentation with Bokashi treated waste

Four months after the completion of the experiment described above, (September to December 2015), the biogas unit was fed with Bokashi treated waste instead of fresh food waste. The mall was also treating food waste with Bokashi, layered with Bokashi bran and stored in 210 dm^3 Bokashi drums which were then sealed and stored for two weeks before being delivered to the composting facility to be composted in windrows. When Bokashi waste was used as a feed for the biogas unit, it was taken from the Bokashi drums which were delivered to the composting facility.

4.3.3.3. Experimentation with simple carbohydrates

The purpose of this study was to observe the effects of increasing the amount of simple carbohydrates (namely bread, pasta, rice or potatoes) added to the feedstock, since it appeared that simple carbohydrates affect the stability of the biogas unit. Firstly, there was a spike (10 kg per day for five days) of only simple carbohydrates fed to the biogas unit. The unit needed to be re-primed and brought back to functionality by re-priming with cow manure. From there, it was reintroduced to food waste, and slowly introduced to increasing amounts of simple carbohydrates with stepwise weekly increases of 2 kg of simple carbohydrates in the total organic waste until the unit was being fed only simple carbohydrates at 20 kg per day. This process took three months. Thereafter, the biogas unit was brought back onto mixed food waste and then given the same spike (10kg per day for five days) of simple carbohydrate food waste.

4.4. Calculation methodology

Since the biogas unit in this study did not all have the same reaction volume, some measured values, like the feed rate and the burning time, needed to be normalised to be used in comparison. The normalised burning time, reported either as a weekly or monthly indicator of the gas burned, was calculated according to Equation 1 below.

$$Normalised\ Burning\ Time = \frac{\sum daily\ burning\ times\ (hrs)}{\sum number\ of\ days\ (days) \times reactor\ volume\ (m^3)} \quad \textbf{Equation 1}$$

From here, the normalised gas use was calculated from normalised burning time by factoring in the gas flow rate of the stove from Table 3, either for the small stove in the domestic installations [D] with a gas flow rate of 0.45 $m^3_{biogas}.hr^{-1}$ or for the large stove in the institutional units [I] with a gas flow rate of 0.72 $m^3_{biogas}.hr^{-1}$ would be calculated according to Equation 2, and has the units of $m^3_{biogas}.day^{-1}.m^{-3}_{reactor}$

$$Normalised\ Gas\ Use = Nornalised\ burning\ time\ \frac{hr}{day.m^3_{reactor}} \times\ Gas\ flow\ rate\ \frac{m^3_{biogas}}{hr}$$ **Equation 2**

Similarly, the normalised feed rate, more commonly referred to as the organic loading rate and was calculated according to Equation 3 and has the units kg.day^{-1}.m^{-3}

$$Organic\ Loading\ Rate = \frac{\sum daiy\ feed(kg)}{\sum number\ of\ days\ (days) \times reactor\ volume\ (m^3)}$$ **Equation 3**

The normalised gas use and the organic loading rate were frequently calculated parameters and used in the analyses as presented in the results chapters.

4.4.1. Confirmation of stove rating and calculation of gas utilisation

This parameter was calculated to give an indication of how much gas was used (estimated from the burning times recorded) as a fraction/percentage of how much biogas would theoretically be produced (given the feedstock provided).

Firstly, the calculation to validate the gas flow rate in the stove is shown below. Based on the specifications provided by Agama that the BiogasPro can store 1 m^3 of gas, which allowed for 2 hours of burning time, the following calculation was undertaken to calculate the number of moles of methane (assumed to be 65% of biogas) using the ideal gas equation (which would hold true at low pressure), as shown in Equations 4 and 5 below.

$$n_{biogas} = \frac{PV}{RT} = \frac{107kPa \times 1000dm^3}{8.3145J/(mol{\cdot}K) \times 298K} = 43\ mol_{biogas}$$ **Equation 4**

$$n_{CH_4} = \frac{0.65\ mol_{CH_4}}{1\ mol_{biogas}} \times 43\ mol_{biogas} = 28\ mol_{CH_4}$$ **Equation 5**

Now, considering the domestic stove, which has a flow rate of 0.45 m^3.hr^{-1}, the number of moles of biogas used in 1 hr would be calculated as shown in Equation 6.

$$\tilde{n}_{biogas} = \frac{0.45\ m^3}{hr} \times \frac{43\ mol_{biogas}}{m^3{}_{biogas}} = 19\ mol.hr^{-1}$$ **Equation 6**

Therefore, the number of moles of methane using the same approach as Equation 5, would be calculated as shown in Equation 7.

$$\tilde{n}_{CH_4} = \frac{0.65\ mol_{CH_4}}{1\ mol_{biogas}} \times \frac{19\ mol_{biogas}}{hr} = 13\ mol_{CH_4}.hr^{-1}$$ **Equation 7**

From here, the heat of combustion of methane is factored in. The heat of combustion for methane is 802.32 kJ.mol^{-1} (NIST, 2012) so the energy yield from the combustion of the methane can be calculated as shown in Equation 8.

$$\tilde{e}_{CH_4} = \frac{802.32kJ}{mol_{CH_4}} \times 13mol_{CH_4} = 10135kJ.hr^{-1}$$ **Equation 8**

From here, converting the energy use to kJ.s^{-1} gives the conversion to the power rating of the stove as shown in Equation 9.

$$10135\frac{kJ}{hr} \times \frac{hr}{60min} \times \frac{min}{60sec} = \frac{2.8kJ}{s} = 2.8kW$$ **Equation 9**

This power rating of the stove supplied by the manufacturer, Puxin Tech is indeed 2.8 kW (Puxin, 2019). For the larger biogas stove, which had a power rating of 4.5 kW, the quoted gas flow rate was 2.5 m^3.hr^{-1}. As mentioned in Section 4.2.1, according to the calculation above, this gas flow rate would have supported a power rating of 15.6 kW. However, a power rating of 4.5 kW would be supported by a gas flow rate of 0.72 m^3.hr^{-1}, so this value was used for the larger stoves when calculating the biogas utilisation.

4.4.2. Calculation of maximum theoretical biogas

In order to calculate the theoretical biogas production, the biochemical methane potential of each of the feedstocks was source from literature. The BMPs used for the calculations are given here in Table 7. Further to this, in the installations where raw sewage was a feedstock, the value assigned to the BMP from sewage was 0.059 kg volatile solids per person in a household per day (Elango *et al.*, 2007)

Table 7. Biochemical methane potentials used for calculation of maximum theoretical biogas

Feedstock	**BMP ($m^3.kg^{-1}$ feed)**	**Source**
OFMSW	0.20	(Munganga, et al., 2010)
Crops	0.28	(Murto, et al., 2004)
Manure	0.18	(Ward, et al., 2008)
Sewage	0.11	(Chynoweth & Isaacson, 1987)

An example of the calculation for the theoretical biogas yield is illustrated as follows. In this example, it was assumed that the OFMSW has a 20% moisture content, i.e. an 80% solids content, and that 90% of the total solids were volatile solids. The BMP for OFMSW from Table 7 (0.20 $m^3.kg^{-1}_{volatile\ solids}$) and the methane content of biogas (65%) was then used to calculate the total volume of achievable biogas (Munganga, *et al.*, 2010). The example is given here with 1 kg of OFMSW to calculate maximum theoretical biogas yield as shown in Equation 10. From here it is shown that the maximum theoretical gas yield is 0.22 m^3 of biogas per kg of OFMSW.

$$1kg_{OFMSW} \times 0.80\,\frac{kg_{total\ solids}}{kg_{OFMSW}} \times 0.9\,\frac{kg_{volatile\ solids}}{kg_{total\ solids}} \times 0.20\,\frac{m^3_{CH_4}}{kg_{volatile\ solids}} \times \frac{m^3_{biogas}}{0.65m^3_{CH_4}}$$

$$= 0.22\ m^3_{biogas}$$

Equation 10

When estimating how much of the gas was actually used, the burning time is used along with the stove rating from Table 3. For example, using the 2.8 kW stove, which has a gas flow rate of 0.45 $m^3.hr^{-1}$. Given a recorded burning time of 20 minutes, the volume of biogas used can be calculated as shown below in Equation 11.

$$Gas\ used = 20\ min \times \frac{1\ hour}{60\ mins} \times \frac{0.45 m^3_{biogas}}{hour} = 0.15\ m^3_{biogas} \qquad \textbf{Equation 11}$$

The gas utilisation is therefore calculated as the estimated amount of biogas used of the maximum theoretical amount of gas produced. In this case, if 1 kg OFMSW was fed into the unit, and the burning time was recorded as 20 mins, the gas utilisation would be calculated as gas used of the maximum theoretical gas as shown in Equation 12. In this case, the gas utilisation is 68.2%.

$$\frac{0.15\ m^3_{biogas}}{0.22\ m^3_{biogas}} = 68.2\ \% \qquad \textbf{Equation 12}$$

These gas utilisations were used as a measure of system operational performance.

4.4.3. Error analysis

Some considerations need to be given here on sources of error. Error may have arisen initially through user precision, for example, with biogas operators making errors in taking pH readings, in the actual reading of the test strip, or in the recording of that information in the application. Error may also have arisen through the calculation process in consideration of the validity of assumptions made, for example, when calculating the gas utilisation, there is an approximation for the biochemical methane potential for the feed based on the nature of the feed, it is further assumed that all the feed is actually converted to biogas, and further, that the biogas has a quality of 65% methane.

Furthermore, the dynamic nature of anaerobic digestion must be acknowledged, specifically that 1 kg of OFMSW fed on a previous day does not automatically translate into 0.22 m^3 of biogas on the subsequent date. It is however noted that over extended periods of time, the dynamics even out, so that total estimated gas volume and total estimated substrate quantity (and even daily fluctuations in properties of the feed) should become less prone to error than individual daily readings.

Lastly, except for Phase 3, it should be acknowledged that the recordings of burning times are not estimations of gas production, but rather of gas use and estimate utilisation. It is thus possible that some digesters in Phases 1 and 2 might have efficient gas production, but that the user at times did not burn the gas and thus lost it. This effect cannot be corrected for from other comments in the data sets.

4.5. Research ethics

Reviewing the operation and monitoring methodology in Phases 1, 2 and 3, many of the proposed studies involved the interaction with people, particularly in the remote monitoring study of Phase 2. That being noted, none of the people interacted with could be negatively impacted through this study.

In Phase 1, the digester was owned by the University of Cape Town, and the monitoring was largely passive. When a low pH reading was observed, it was corrected for and this was by and large the extent of the interaction. In Phase 2, there was passive monitoring of data which was submitted by biogas operators in remote locations. Upon observation of a low pH event, the operator was contacted for further information on what may have caused it. Again, this was passive data gathering, so there was no risk of harm to any person. The final biogas unit used in Phase 3 was run according to a prescribed feeding regime with active management through the remote monitoring system. The research approach and methodology for all studies was submitted to the Ethics in Research council at UCT and approval was granted accordingly as shown in Appendix E.

4.6. Outlook

The methodology proposed takes the following approach. Firstly, observational research on one biogas unit to inform initial learnings around productivity and stability, and to develop a remote monitoring toolkit to capture data from small-scale biogas units in urban settings. The method for measuring parameters to infer operational data (to inform productivity and stability) is evaluated. These form the body of Phase 1 and the results and discussions around this are presented in Chapter 4. This toolkit is then used to gather data from ten biogas units across southern Africa. This remote monitoring work is Phase 2 and is presented in Chapter 5. After the analysis of this data, theories are generated and specific experimentation to inform these theories is undertaken on one biogas unit in a controlled environment. These sets of experiments are Phase 3 and are presented in Chapter 6.

Thus, the approach across the phases will broadly and specifically speak to the potential and limitations of small-scale biogas operations in urban Africa. The hypotheses generated speak to the stability and the productivity of such small-scale biogas units, as well the potential need for remote monitoring as knowledge support to safeguard investment.

Chapter 4: Initial Field Observation

The UCT biogas unit, a 6 m^3 Agama BiogasPro (Agama, 2010) was commissioned in February 2011. The first set of observations on this small-scale biogas unit was carried out from March 2011 to February 2012. The UCT biogas unit was also used to inform the development of the mobile phone application for Phase 2, the remote monitoring study presented in Chapter 5. The operation of the unit followed the methodology outlined in Section 4.3.1. Aspects of this study were presented at WasteCon 2012 (Naik, *et al.*, 2012) with abstracts in Appendix G1. The full operational experience of this biogas unit is presented here in Section 4.1. Section 4.2 presents evaluation of the different sampling methods used, while Section 4.3 describes the refinement of the Biogas Monitoring Tool application which was piloted on the UCT biogas unit for use in Phase 2. A summary of the findings and discussion on how these findings speak to the first and second hypotheses presented in the previous chapter are presented in Section 4.4.

4.1 Observations on unit stability, pH and feeding regime

Referring back to Table 5 in Section 4.3.1, reproduced below for ease of reference, the first three months (Period 1), involved the start-up phase and the stabilising of the system. In this time, the lime buffer was used three times when the pH was detected to be below 6.0 as shown in Figure 10. These points were recorded along with the other normal readings. In this period, the mass of food waste fed to the reactor was also reduced if the pH crossed below the 6.0 value.

Over Period 2, no buffering was needed, but the mass of food fed to the biogas unit was throttled whenever the pH seemed to be declining. Over Period 3, buffer in the form of lime was used on four occasions to stabilize the pH as in Period 1. In Period 3, the feeding regime was not throttled when there was an incidence of low pH. There was an eight-week hiatus between Period 3 and Period 4, after which there were no further records of instability with respect to pH and no interventions necessary since resumption of feeding in late January 2012. However, it must be noted that the method of monitoring pH changed from the start of 2012 (indicator strip vs pH probe).

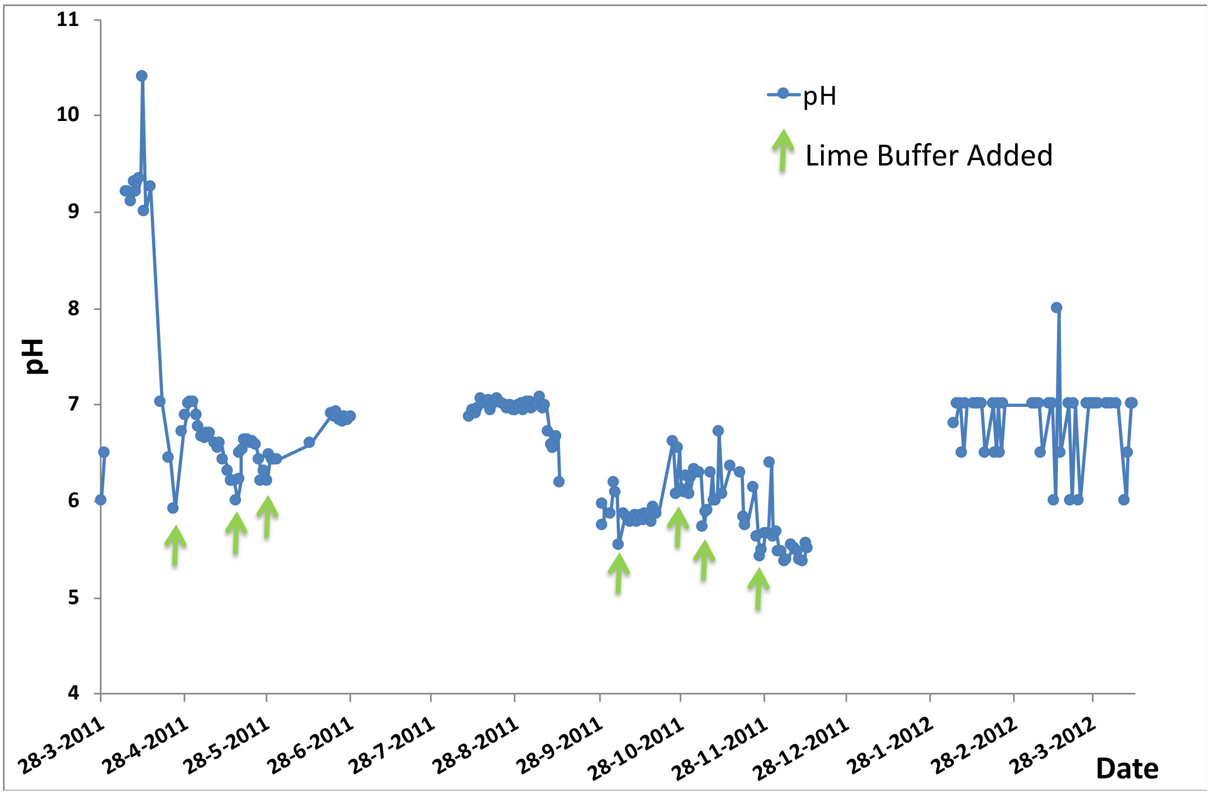


Figure 10. Trends in pH (•) for the UCT biogas unit in Phase 1, between March 2011 and April 2012

It is noteworthy that while the pH remained relatively unchanged over the long break between Periods 1 and 2, there was a marked decrease between Periods 2 and 3, although it does appear that the pH was already decreasing at the point, whereas it was stable formerly.

The mass of food waste fed, along with the respective volume of water added to the unit are shown in Figure 11.

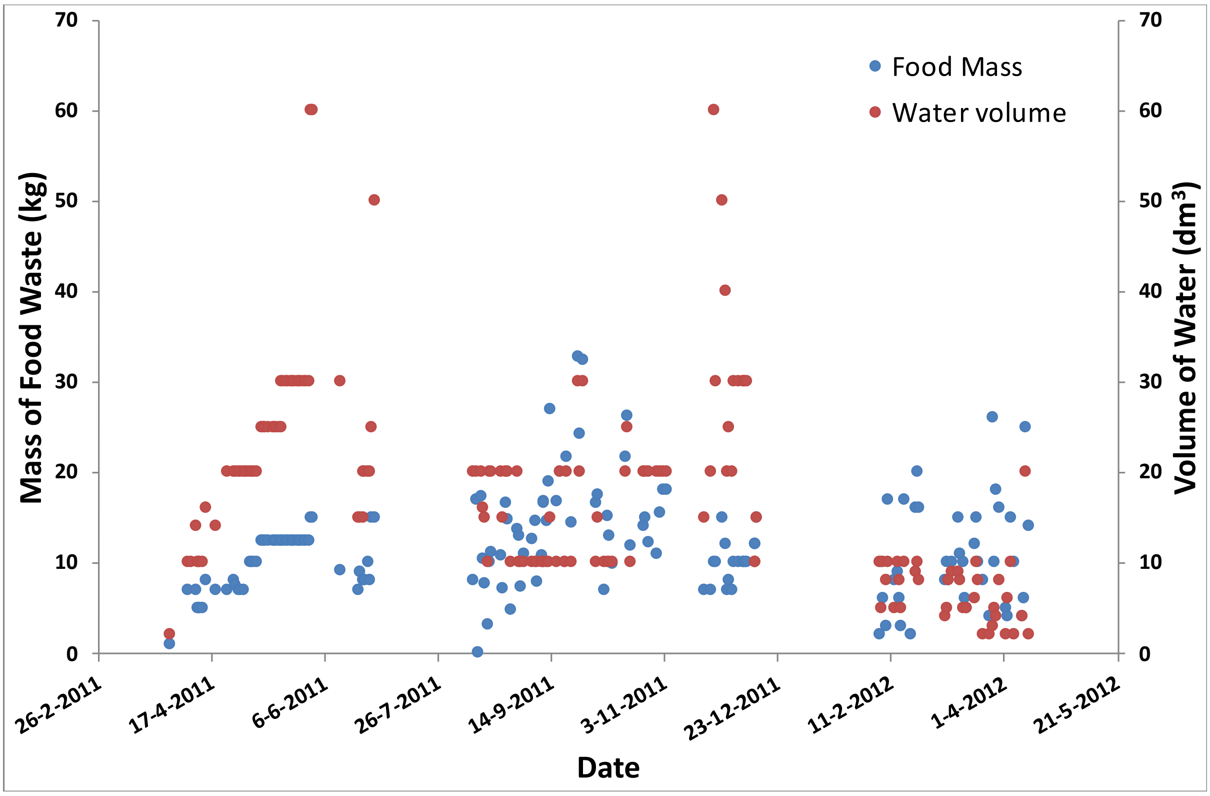


Figure 11. Trends in food mass (●) and water volume (●) fed to UCT biogas unit in Phase 1, between March 2011 and April 2012

For Periods 1, 2 and 3, the volume of water added to the biogas unit was typically more than the amount of food waste added to the biogas unit. In Period 4, there was much less water added to the biogas unit, which meant that there was a longer hydraulic residence time. While it was noted that the sampling method for pH changed, it was also observed that the was an increase in hydraulic residence time in Period 4, which may also have contributed to the improved stability of the biogas unit.

4.1.1 The effect of feed regime effect on stability

In this initial work, the pH was used as an indicator of the stability of the biogas unit, considering it as a whole system. Between Figure 10 and Figure 11 and 2, it is noted that the initial decline in pH at the beginning of Period 1 occurred even while the feed rate was very low. However, after the system was buffered, it stabilized until June with the constant feed rate of 12 kg per day. Granted, there were two further occasions when lime was added as a buffer, but on the whole, the system was relatively pH stable. Over Period 2, the amount of feed added to the reactor was decided based on the current feeding regime and the pH of the system. If the pH was decreasing to 6.0 and addition of lime seemed imminent, less food was added to the biogas unit. In other words, the organic loading rate was reduced when there were observed drop in pH. Therefore, with close monitoring of the operating conditions of the reactor, relatively stable operation was achievable. Over Period 3, the system was only buffered when the pH dropped below 5.5. Pseudo-stable operation was achieved at a lower operating pH, but this time with the addition of lime at key points. The slightly higher masses of food added in this period (often close to 20 kg) was likely to have been the factor that caused this drop in pH. Over Period 4, there was stable operation in the optimum range between 6.5 and 7.5. On the four occasions when the pH did drop below 6.5, it was noted that two days before these episodes, the feedstock was always typically high in simple carbohydrates and often only contained simple carbohydrates, namely; “rice & pasta”, “pasta & vegetables”, “bread & pasta” and “rice & bread” respectively. Over Period 4, the decrease in the volume of water fed to the digester would have significantly affected the hydraulic residence time of the food waste in the digester. The increase in hydraulic residence time, as a direct result of lower amounts of water fed to the digester could be the reason for the improved stability of the biogas unit.

Thus, attention needs to be paid to the effect of the type of food waste on the pH. This is why the type of food waste fed to the unit was recorded. The reason for this, is that prior to the study, the reactor was fed with waste from the breakfast meal, which consisted largely of discarded bread. The pH was seen to plummet and the unit needed re-inoculation with cow manure before this study was carried out. Also, the OFMSW was switched to canteen waste from the lunch meal as opposed to the breakfast meal. Furthermore, it was attempted to ensure that there was a fair amount of protein to reach a C:N ratio of between 20 to 30 wherever possible. This was not always achievable and sometimes only a carbon source was added. If the carbon source was all simple carbohydrates, then the above described reduction of pH was noticed. Typical feedstock over the entire period was often a mixture of rice or bread with chicken, beef or eggs and often some salad or other vegetables. It should further be noted that towards the end of Period 3, the feed was sporadic and typically a small amount of almost entirely vegetables most often accompanied by some form of carbohydrate. Over these times, there was noted decrease in the amount of gas produced and this is why the burning time measurements were not performed over Period 3.

4.1.2 Observations of temperature

The temperature over the entire Periods 1, 2 and 3 fluctuated between 15 and 20 °C. The temperature is not seen to influence the stability of the system, but it may very well have an effect on the system's productivity, i.e. the volume of biogas produced. The Biogas Monitoring Tool application was refined to include burning time as discussed in Section 4.3 in order to quantify productivity and determine this effect. Further discussions on productivity, however, are presented in Section 4.1.3.

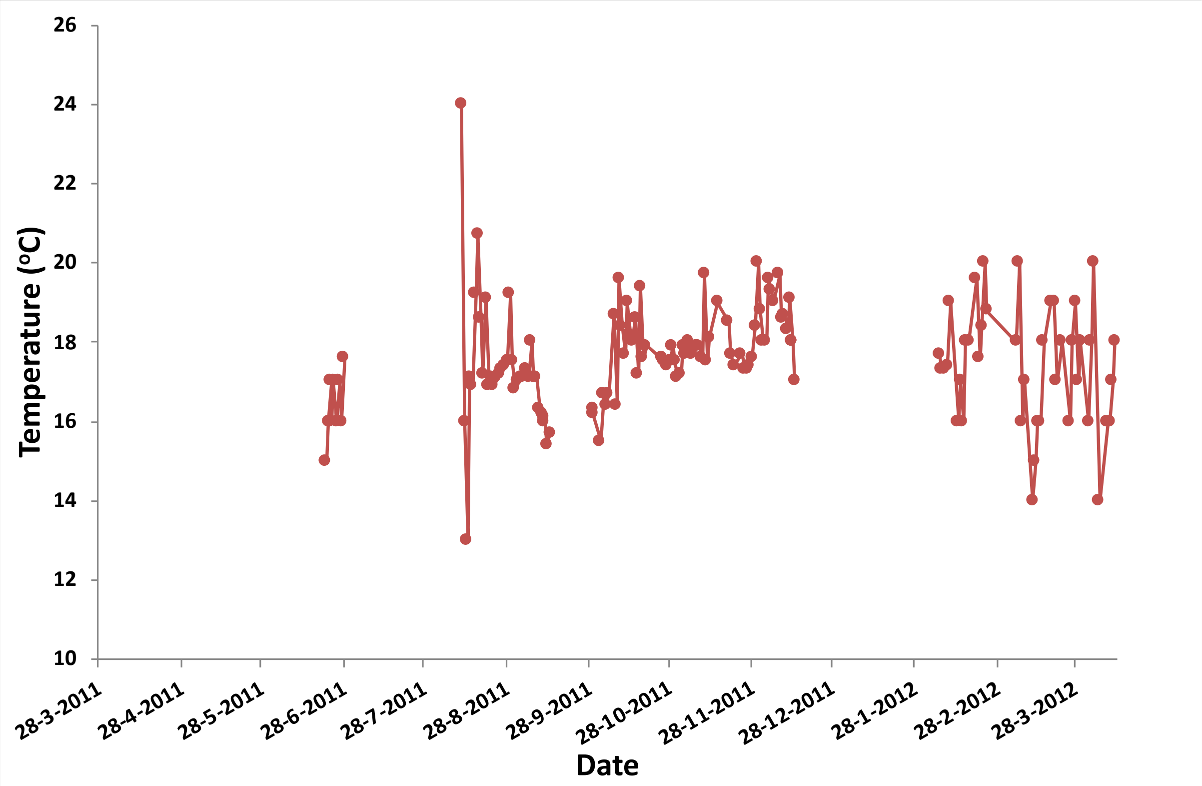


Figure 12. Temperature measurement (●) of the UCT biogas unit in Phase 1, between March 2011 and April 2012

Here, it is noted that there is greater fluctuation in temperatures in Period 4, which have been taken from daily mean temperatures for the City of Cape Town (from the Cape Town International Airport meteorological station) as a whole reported and published by the municipality, compared to those measured specifically at the biogas unit with a probe over the Periods 1, 2 and 3. Further investigation of the suitability of the reported weather data is presented in Section 4.2.2.

4.1.3 Gas utilisation and productivity

For the five weeks where burning times were recorded in Period 2, burning of biogas was only performed on weekdays. The readings were taken from Wednesday to the following Tuesday to include the gas produced over the weekend. A summary of the total amounts of gas used as well as the gas utilisation (as calculated from Equations 10, 11 and 12 in Section 4.4.1) yielded in that week are shown in Table 8. Week 1 and week 4 each reported an instance of a daily burning time of over one hour accompanied by a 4 kPa – 5 kPa drop in pressure of the system. The average utilisation over this five-week period is 41%, thus it is already noted that not all of the food being fed to the unit was converted into biogas utilised in the kitchen, meaning that depending on the hydraulic residence time, there was possibly more potential for energy generation from organics in the unit effluent, accumulation of organics in the reactor and/or that any extra gas produced was vented into the atmosphere if the gas pressure reached maximum.

Table 8. Burning times over five weeks in Period 2 for the stove connected to the UCT biogas unit in Phase 1

Week	Total burning time (hrs)	Total food waste (kg)	Gas Utilisation (%)
1	2.5	56	40
2	2.0	42	43
3	1.9	38	45
4	3.5	71	45
5	1.0	29	31

Over the ten weeks in Period 4, the cumulative burn time was calculated from the summation of reported burning times from the smartphone application. The application asked for cumulative burning time since the last use in minutes. A summary of this data and conversions is shown in Table 9. The average gas utilisation over the ten-week period is 51% and most efficiencies over this period are better than those over Period 2, barring weeks 5 and 9 in Period 4.

Table 9. Burning time over ten weeks in Period 4 for the stove connected to the UCT biogas unit in Phase 1.

Week	Total burning time (hrs)	Total food waste (kg)	Gas Utilisation (%)
1	2.5	38	59
2	2.4	43	50
3	3.6	54	60
4	2.1	36	53
5	1.8	47	35
6	2.6	45	52
7	3.8	74	46
8	2.5	34	66
9	2.7	67	36
10	1.4	24	53

Typical use of the gas was to prepare a meal for the vegetarian meal option, which took 20 – 30 minutes, hence use of the gas was typically not much more than 3.5 hrs.week^{-1}. It is therefore postulated that there could be more production of gas if the feeding rate was increased and there is still potential for better utilisation of the gas produced.

4.2 Evaluation of monitoring techniques

The UCT biogas unit was also the test unit for which the remote monitoring methodology was trialled. There were two key aspects to this. The first, was an evaluation of the monitoring techniques, specifically for acidity and temperature, to determine whether more simple and crude measurement techniques would be suitable as replacements for the refined laboratory level techniques. These are presented in Section 4.2.1 and 4.2.2 respectively. The second, was the development and then the refinement of the smartphone application to collect the data from the various biogas units. This is presented in Section 4.3.

4.2.1 Evaluation of pH monitoring methods

Data was gathered from three separate units at separate timeframes. The UCT data was gathered from October to December 2011. Data was gathered by one of the remote monitoring users (Unit 4) from the Eastern Cape (EC) during 2014. As there was a concern that these data sets, were somewhat limited to conclude that pH strip measurement was sufficiently robust, a final set of data was gathered over April and May 2019 from the digester at N1 City Shopping Mall (N1). In each case, a user submitted recorded pH readings from indicator strip, and this was compared to the measured pH by the probe. In the last case, the data from the probe was obtained from The Waste Transformers (Waste Transformers, 2018) office in the Netherlands. This data is presented in Figure 13.

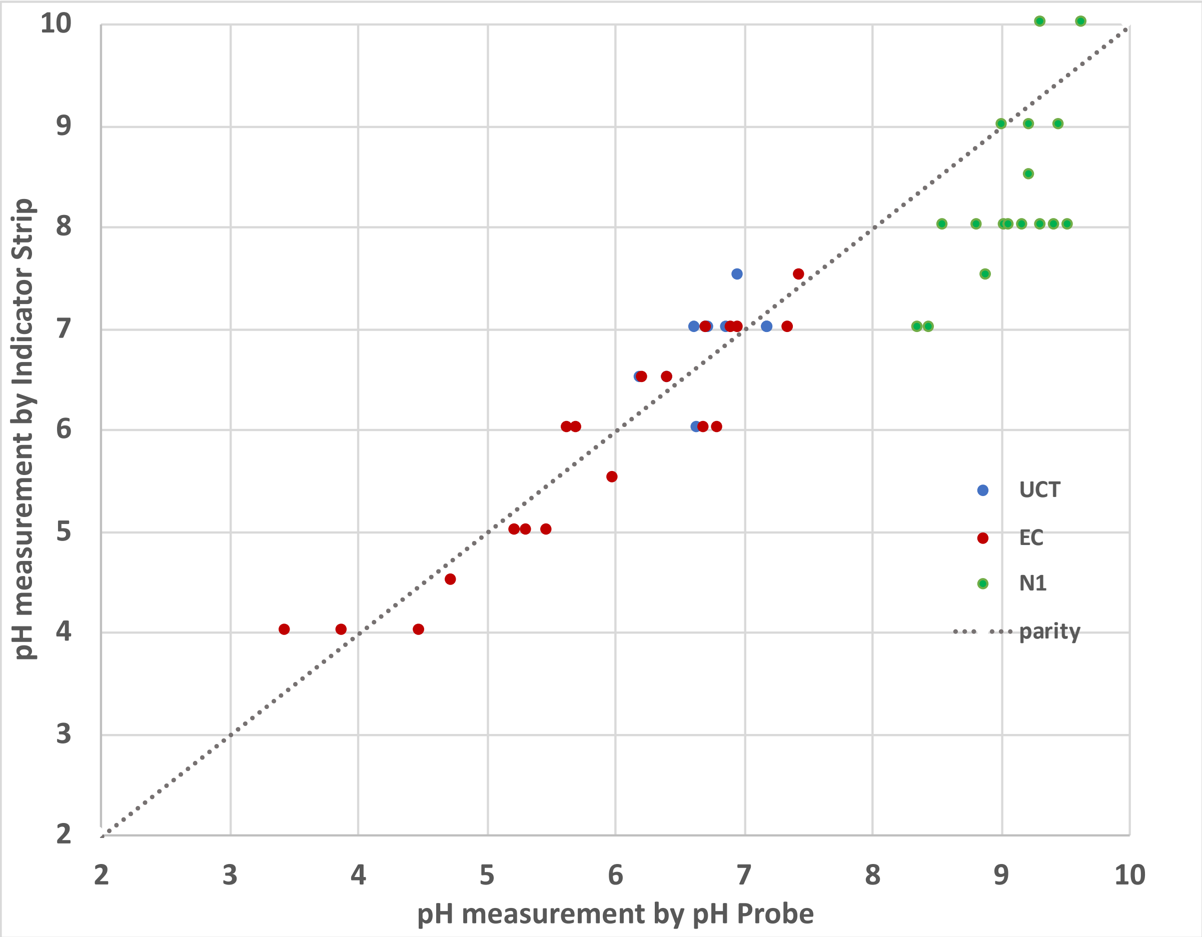


Figure 13. Parity plot of pH measured by indicator strip vs probe for the UCT biogas unit (●), the Eastern Cape biogas unit (●) and the N1 City Shopping Mall biogas unit (●).

It is understood that because the indicator strip measurements are based on human interpretation of the colour scale, not numerical measurements, there is some likelihood of observational error arising. Notably, in the case of N1 City, when the pH was in the higher ranges, there appears to be an underestimation of the pH using the indicator strip, or a problem with the calibration of the pH meter. In any event, during this monitoring period, this digester had an unusually high pH over the entire range of monitoring.

A summary of this analysis is presented below in Table 10. There are 29 readings below (and including pH 7) with a mean difference of 0.39 and a standard deviation of 0.34 pH units. Furthermore, the 17 readings below pH 7 have a mean difference of 0.38 and a standard deviation of 0.22. It could also be possible that the data in the lower range is more accurate because the user is more invested in taking accurate readings as the digester was in a recovery, or that the indicator paper allowed a higher level of accuracy at lower pH ranges.

Table 10. Analysis of absolute mean and standard deviations over the pH ranges for pH indicator strip vs. pH probe measurements.

Range	Data points	Mean Absolute Diff.	Std. Deviation
All	46	0.54	0.44
≤7	29	0.39	0.34
<7	17	0.38	0.22

A t-test was carried out using the statistical analysis tool in MS Excel to determine whether the null hypothesis holds, i.e. that there is no significant difference between the sampling methods and that any observed difference would be due to sampling or experimental error. The test was carried out on each data set as well as the entire data set as a whole. The results from the test are shown below in **Error! Reference source not found.**. The results show that there is indeed differing confidence levels across the various data sets.

Table 11. Results of t-test analysis of pH data measurements by indicator strip vs. pH probe.

Data Set	Data Points	T Stat	df	P(T≤t)
UCT	10	0.51	17	62%
EC	19	-0.29	36	77%
N1	17	-3.5	22	0.20%
All	46	-1.00	88	32%

Results from the t-test show that there is the most confidence in the data from the EC biogas unit, as suspected from the higher accuracy in observations. Notably, these were at lower pH readings. There is the least confidence in the data from the N1 City Shopping Centre biogas unit. This unit was not part of the original study as it was only installed in late 2018. The reason for using this unit was to generate more confidence in the use of pH indicator strip in lieu of the pH probe, but it appears that the results from this set of data have done the opposite. This digester was suffering from a high alkalinity at the time of observation. While this was useful to obtain a full range of data (as there were no data points above a pH of 7.5 until this data set was introduced) it showed high levels of inaccuracy at higher pH levels. This unit is unique in that it is monitored remotely from the Netherlands and also that the pH indicator strip readings were taken by a commercial relationship manager, rather than a biogas unit operator, as they were for the other studies. The reasons for the higher levels of inaccuracy could be attributed to the user; to a shortcoming of testing method (i.e. the indicator strip not allowing for differentiation at higher pH readings); to an uncalibrated pH probe; or in part to some or all of the factors mentioned.

For the purpose of this study, since all the pH readings of the biogas units monitored were at 8.0 or below, the data from the N1 City digester was disregarded. Looking at the UCT and the EC biogas units, the probability that the measured value from the indicator strip would be within 1 standard deviation of the value measured by the pH probe was at 62% and 77% respectively, with those for a digester in distress being higher than for one operating under good conditions. It was decided that this level of precision was acceptable for the purpose of this study and the pH measurement via indicator strip was used in the monitoring study in Chapter 5.

4.2.2 Evaluation of temperature monitoring methods

Temperature readings at the UCT digester were taken over four months with the temperature probe according to the methodology outlined in Section 4.2.3.2 and compared to the average daily temperature reported by AccuWeather (Accuweather, 2012) from the meteorological station at the Cape Town International Airport, and shown below in Figure 14. There were 92 readings in total, with the measured temperatures consistently 1 °C to 3 °C lower than the weather report. The mean difference between the measured and reported temperature was 1.4 °C with a standard deviation of 0.9 °C - typically lower for the measured temperature. These readings are plotted against each other as a parity plot in Figure 15 and then as a time series in Figure 15.

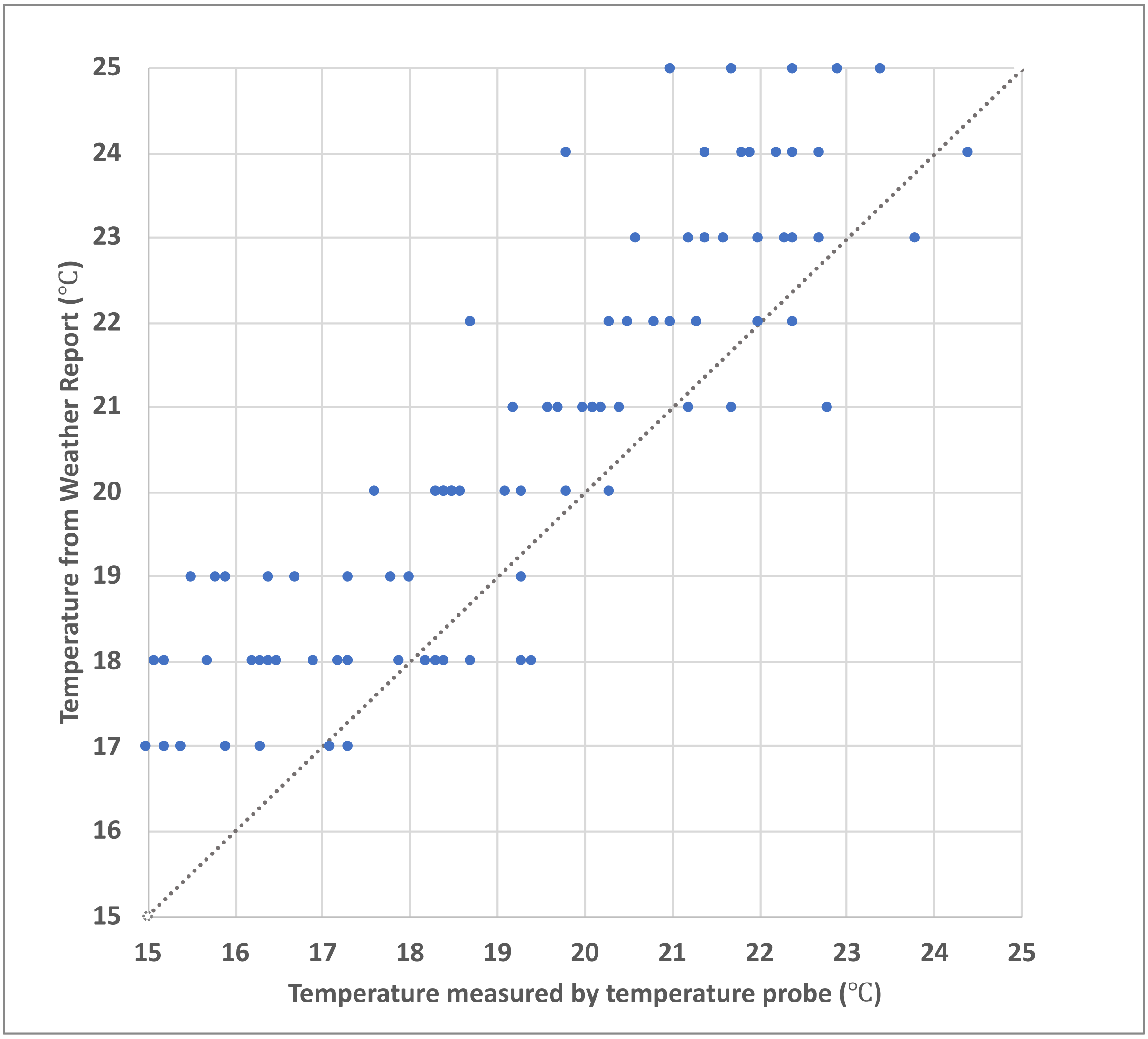


Figure 14. Comparison of reported and measured temperature readings for the UCT digester.

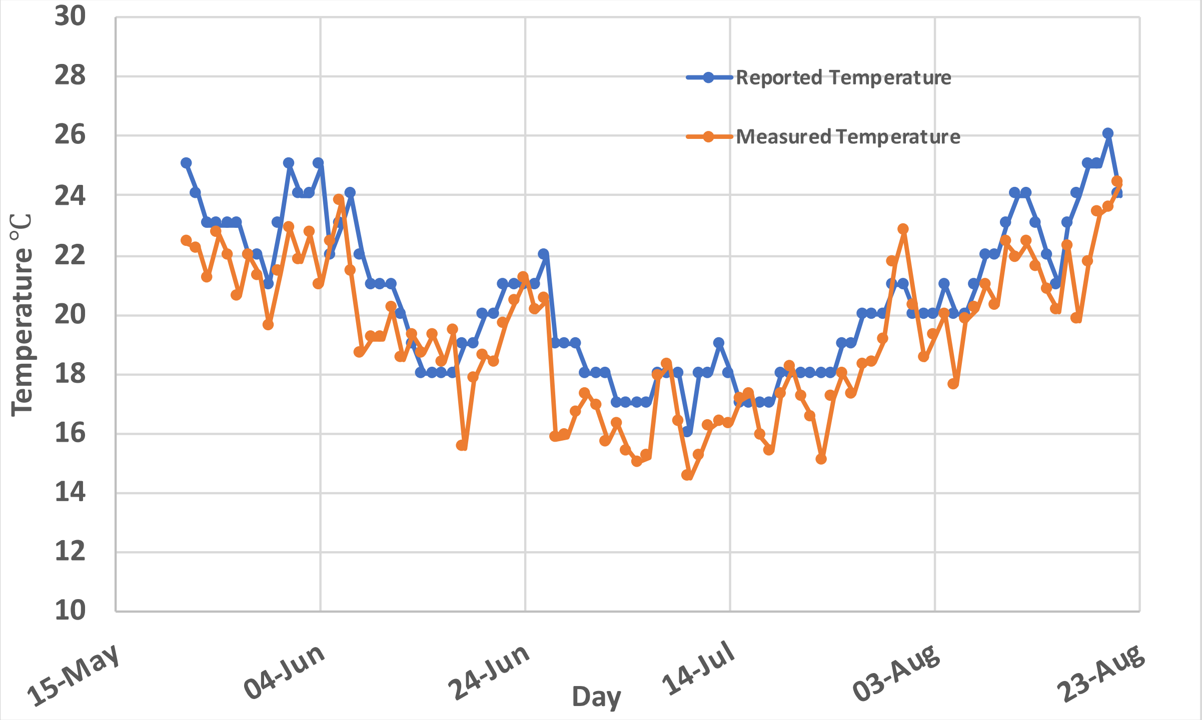


Figure 15. Reported (●) and measured (●) temperature readings for the UCT digester over a 92 day period.

A t-test was also conducted on this data set. There were 92 readings and a t-stat value of 3.1, with a df of 182, resulting in a P(T≤t) of 0.1%. The t-test would test the hypothesis that there is no significant difference between the two sets of measured values. This hypothesis was therefore rejected with the results of the t-test. Further consideration was therefore given to this data set as follows:

- There is a comparison between a daily mean, and a measurement taken at one particular time of the day. For example, the temperature profile over a day can vary by 10°C or more. However, temperature readings for the biogas unit were taken typically between 10:00 and 12:00 noon, when it would be expected that the temperature would be lower than the daily mean.
- The daily mean temperature would be for a town/city, which itself would have different temperature profiles in different suburbs. The reported temperatures are taken from the airport meteorological station.
- The biogas unit was in the ground and would possibly be better approximated by ground temperature than ambient temperature. Ground temperatures vary from being slightly warmer than ambient temperatures when there is fertile

soil with an active microbial population, to being slightly colder for less fertile soils. (Bharadwaj & Bansal, 1981; Mann & Schmidt, 2003)

- The biogas unit could be in the sun or the shade, which would have an influence on ambient temperature, and on the temperature of the biogas unit.
- The sampling point in the digester was close to the surface of the unit, not in the centre of it.

With the above in consideration, while factoring in the offset of 1.4 °C , and noting from Figure 15 that the reported temperature does track the measured temperature over the entire date range as the temperature fluctuates, reported weather data was taken as an acceptable measurement for the approximate digester temperature.

4.2.3 Other monitoring methods

Weights of food and water were recorded as described in Section 4.2.3.3 and the burning time was occasionally recorded to estimate the gas utilisation. The burning time was not originally included in the first build of the application but was done so from January 2012 to allow utilisation efficiency calculations to be included.

4.3 Refinement of the Biogas Monitoring Tool application

The mobile phone application used, was developed as described in Section 4.2.2. The final digital form presented in that section was the result of an iterative process based on learnings with the UCT biogas unit. Initially, the digital form was created to allow individual users to submit data obtained. In the first build, there were 5 input options, all as free text and listed as follows:

- Date
- pH
- Temperature (°C)
- Mass of food fed (kg)
- Pressure (kPa)

In the later builds, it was decided to refine the parameters reported. Firstly, the date and time were taken directly from the mobile phone to reduce error in reporting. The recording of the Pressure gauge reading was removed from the criteria for reasons discussed in Section 4.2.3.4. In some cases, samples of the digestate were taken, so this was added as a Yes/No selection. Additionally, it was noted that the quality of the flame was an indication of gas quality and so a second selection was added to select the flame quality. Finally, in order to glean insights into the feedstock, particularly for OFMSW, a free text input was added. The final inputs are shown in Table 4 from the methodology section, reproduced below for ease of reference.

Table 4. Parameters reported through the Biogas Monitoring Tool application in Phase 2.

Parameter	**Method of measure**	**Input by user**
Date	From phone	None
Mass of feed	Weighed or estimated	Number input only
Description of feed	Observation	Free text
Volume of water added	Weighed or estimated	Number input only
pH	Indicator strip	Number input only
Pressure	Recorded from in-line pressure gauge	Number input only
Burning time	Estimated	Number input only
Flame quality	Chosen from list as follows: • Stable blue • Yellowish • Unstable	Selection
Sample taken (of digestate)	Chosen from list as follows: • Yes • No	Selection
Username	-	Free text
Temperature	From weather report	None

4.4 Final discussions and conclusions

Instability of the biogas unit was observed in all four periods. The mitigation technique adopted in Periods 1 and 3 was the addition of lime. However, close monitoring of the pH and adjustment of the organic loading rate proved to be effective as well, avoiding the need for lime in Period 2. Finally, a hiatus in feed before Period 4 appeared to improve the stability of the unit which did not need buffering or strict control of the organic loading rate in Period 4. This is with the note that two variables were different in Period 4, namely that the volume of water fed to the unit was significantly lower than previous Periods, and that the method of monitoring pH (i.e. stability) was less precise as it was with indicator strip rather than pH probe.

Temperature was merely observed in this study and not linked to gas production or utilisation. Gas utilisations were conducted over two separate periods, namely over five weeks in Period 2 and over ten weeks in Period 4. The utilisation was on average 10% higher in Period 4 (which was in summer) than in Period 2 (which was in winter). This is not conclusive of higher gas production just utilisation. Low utilisations are an indication that there is more gas available than is being used and the hydraulic residence time would need to be factored in to conclude on this.

The use of a mobile phone application to report data was trialled in Period 4. The initial parameters chosen for monitoring were refined over the course of the development, for example, pressure gauge readings were not deemed to be useful indicators, while flame quality was added to the list as a measure of gas quality. Considering that the laboratory measurement of pH and temperature were taken at sampling points of less than a metre in the inlet pipe (not in the centre of a mixed reactor), acceptable confidence was bestowed to the substitution of laboratory measuring techniques for pH and temperature with indicator strips and reported weather data respectively. In this study, the remote monitoring methodology was able to generate data sets through more simple measurement techniques. Whether the data sets are still useful remains to be determined.

Chapter 5: Remote Monitoring Studies

The key engineering contribution of this thesis lies in the attempt to develop a remote monitoring and knowledge support tool for the operation of small-scale biogas units. The tool was developed as described in Section 3.2.2 and used in this study in an attempt to address Hypotheses 1 & 2; which were around biogas unit stability being affected by the feedstock, and the productivity being affected by the temperature respectively. The study was undertaken to gain an understanding of actual performance of installed units in various locations, and specifically to understand factors which affect their productivity and stability. This facilitated the refinement of the monitoring techniques and gave confidence in the methods chosen. The second study took these smart monitoring learnings and applied them to ten units around southern Africa, as described in Table 2, Chapter 3.

5.1 Stability of biogas units

The stability of biogas units was analysed on a case by case basis. It was noted that whenever the pH gave a reading below 6.0, the user was contacted to ascertain whether any assistance could be offered in the feeding regime. This was facilitated by an update to the user interface mentioned in Section 4.2.2 which turned location markers in Figure 7 from “green” to “red” if the last pH data point sent through was less than 6.0. Typically, the user was contacted at that time and questioned about any changes to the feeding regime of the biogas unit. The feeding regime of the previous two weeks was also analysed to determine possible causes for the instability in order to inform Hypothesis 1, which postulated that the feeding regime would be significant in the stability of small-scale biogas units.

5.1.1 Biogas unit pH vs time series

The pH value was monitored for each biogas unit. The results for all ten biogas units are shown from Figures 16 through to 25. The profiles show that the units operated mostly between a pH of 6 and 8, but a closer analysis shows that all the small-scale biogas units in this study experienced instances of pH readings below 6 at one or more times. For ease of reference, an orange line has been drawn at pH 6.5 and a red line has been drawn at pH 6.0 on each graph to easily show which readings fall below pH 6.0. The profiles also show where there were gaps in data from users. The request of the users was to submit data at any time the digester was fed, so that there would be no missing information when calculating other parameters.

5.1.1.1. Individual pH profiles of all units

The acidity vs time profile for 1.(WC).6.[O].[I] is shown in Figure 16. There were five readings which were below a pH of 6.0 and these occurred over four separate periods.

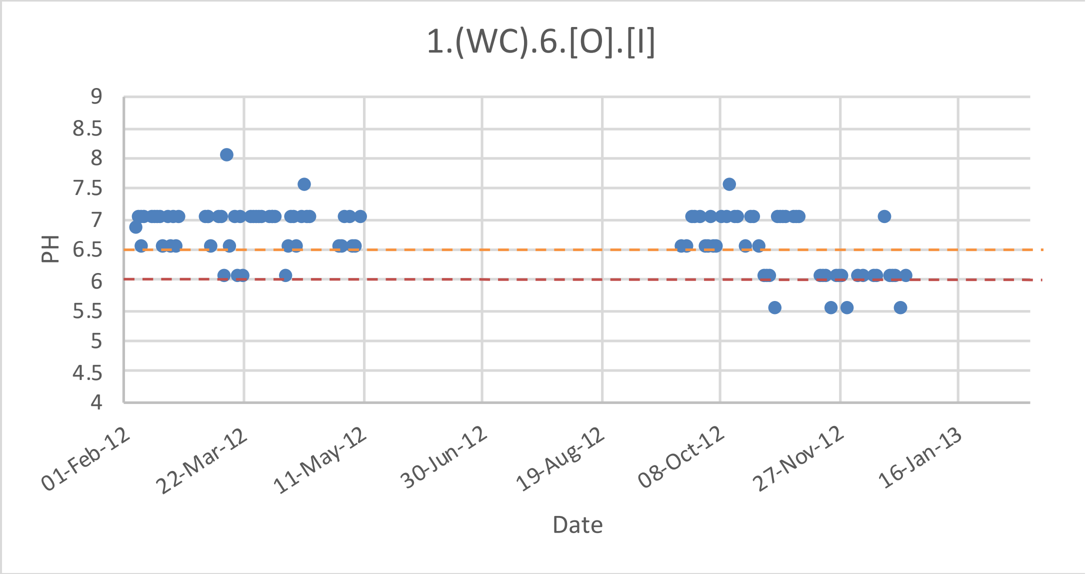


Figure 16. pH vs time series for 1.(WC).6.[O].[I] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

There was a gap in data sent by 1.(WC).6.[O].[I], the UCT biogas unit. There were four episodes when the pH was below 6.0. Analysis of the feeding regime 3 to 7 days before each instance of pH decline revealed the following, as shown in Table 12.

Table 12. Extraction of data recordings of feeding regime of 1.(WC).6.[O].[I] before instances of a decline in pH.

Date	Mass (kg)	Food Description
21 October 2012	10	Bread, Pasta
08 November 2012	18	Bread, Rice
29 November 2012	48	Bread, Rice, Veg
21 December	34	Rice

From observation, it has been noted that in every case, there was an instance of a large amount of a simple carbohydrate (most often not mixed with anything else), fed to the digester before the decline in pH. Furthermore, these instances which resulted in a decline in pH where a large amount (more than 10 kg) of simple carbohydrates were fed into the biogas unit, were the only instances where this feeding regime (a large amount of simple carbohydrates) was apparent.

2.(WC).10.[O].[I], was a biogas unit at a community garden in Cape Town. The unit was donated as a demonstration plant and was fed almost exclusively with vegetables and kitchen scraps from vegetable preparation. The pH vs time profile is shown in Figure 17.

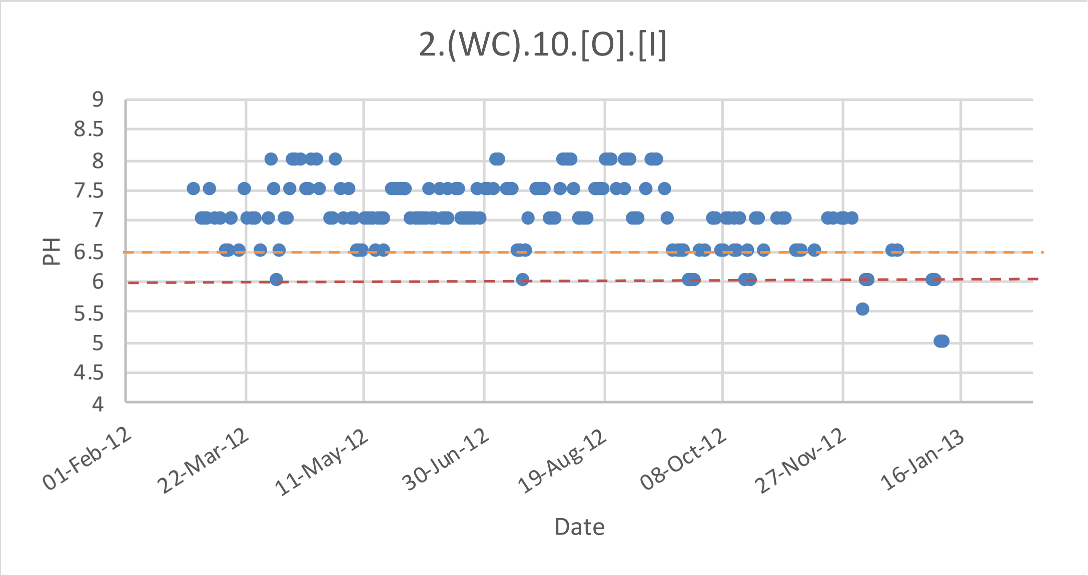


Figure 17. pH vs time series for 2.(WC).10.[O].[I] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

For most of the monitoring study, the pH of this biogas unit remained healthy. There was one instance of a pH recording below 6.0 in early December 2012, and two consecutive days in early January 2012 when the pH was observed to be below 6.0. There is no apparent reason for the low recording of 5.5 in December 2012. Indeed, the unit appears to have recovered from the low pH just two days later. The last feed in 2012 was on 21 December 2012. In the first week of January, the digester was fed with spoiled bread dough which was not used before the holidays. This was the only instance when the biogas unit was fed with something other than the usual vegetable waste and canteen waste and is likely to have been the cause of the low pH observation in the subsequent week.

3.(WC).6.[O][S].[D] was also in the greater Cape Town area. It was connected to a domestic sewage outlet so there was an additional feed substrate by way of raw sewage. The pH vs time profile is shown in Figure 18. There was a short spell in September 2012 with low pH, once in mid-October 2012 and then once in late December 2012.

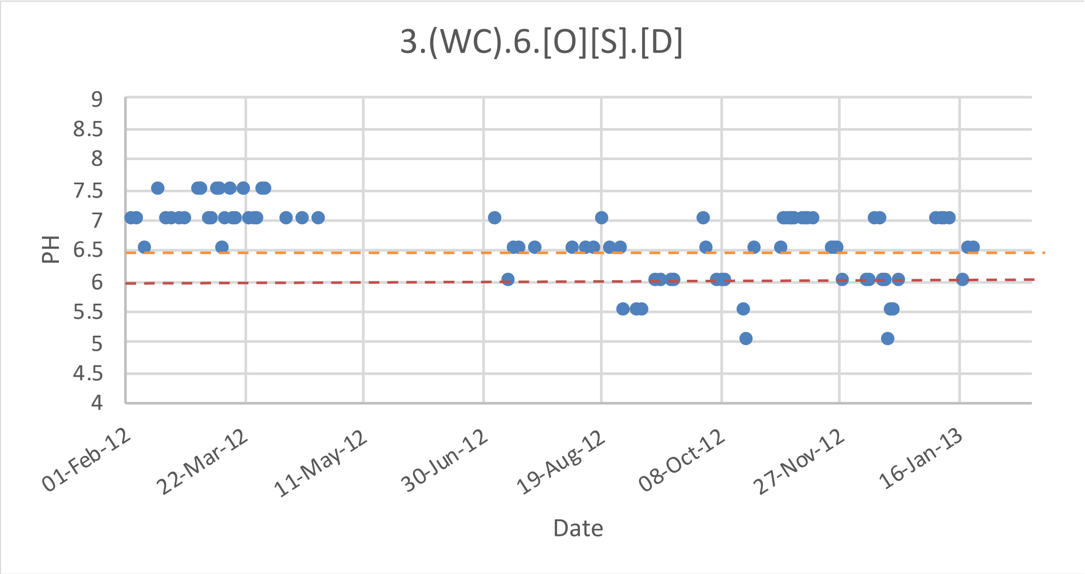


Figure 18. pH vs time series for 3.(WC).6.[O][S].[D] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

The first episode was a two-week period over August and September 2012 in which the biogas unit was recovering from a shock. Here, the shock was not a spike in a large amount of simple carbohydrate, but rather a change in the feed to the biogas unit. It was noted that over this period, the largely vegetarian household had guests who were meat eaters. This had two effects. Firstly, the increase in occupancy meant that there was more sewage entering the digester, secondly, it is possible that the food waste being fed changed in nature too, causing a perturbation to the otherwise steady state. Interestingly enough, this same effect was noted in mid-October and also over the December vacation when the household had guests again. It is certainly noteworthy that the presence of guests had a noticeable effect on the stability of the biogas unit.

4.(EC).6.[O][S].[D] was a domestic installation in the Eastern Cape. It had the same type of feed as the third unit in the Western Cape as it was also a domestic installation connected to the sewage outlet. The pH vs time series for this unit is shown in Figure 19. Of all the units monitored, this unit was plagued with the most episodes of the pH dropped below 6.0. In fact, the operator bought a pH probe and monitored the pH through recovery periods, which provided one of the data sets for the pH comparison in Section 4.2.1.

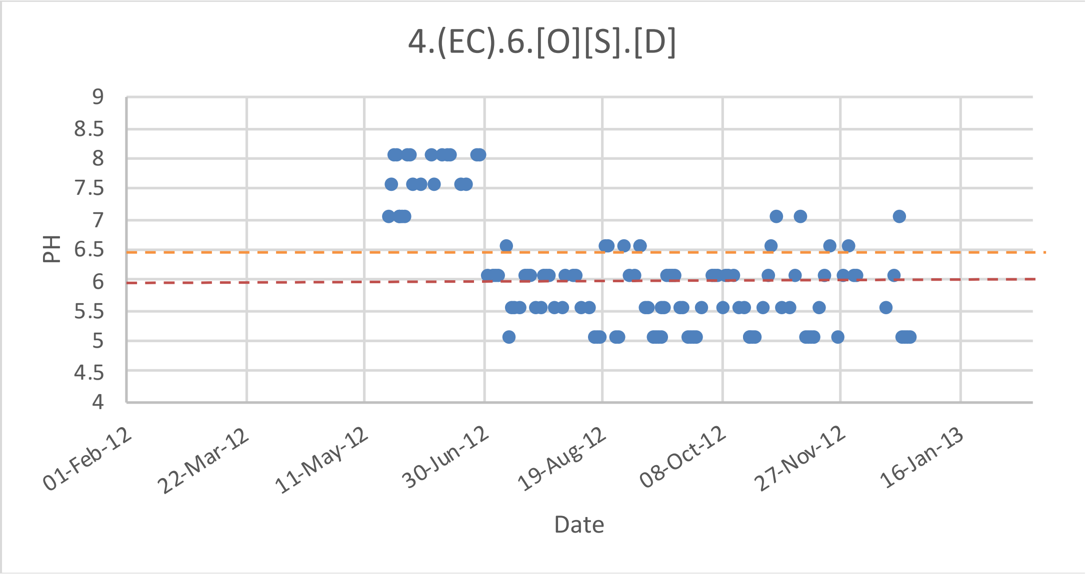


Figure 19. pH vs time series for 4.(EC).6.[O][S].[D] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

Contact with the user revealed that the operator was struggling to get the unit running efficiently. It was postulated that the digester was being fed too much raw sewage, but it was never resolved. This user was unable to generate biogas of a good enough quality to cook from. The flame produced at the stove was unstable and often never held.

5.(SWZ).6.[O][S].[D] was a similar domestic installation, fed with sewage and organic waste in Swaziland. This was the only unit not in the Republic of South Africa. The pH vs time series is shown in Figure 20. There were two main periods when data was sent through. In the first period, from April to August 2012, there was relatively stable operation. The unit was then not used for a short while. From November 2012 to January 2013, the operator conducted their own set of experiments on the digester, trialling out different feed substrates (such as dairy only, and once even some agricultural waste).

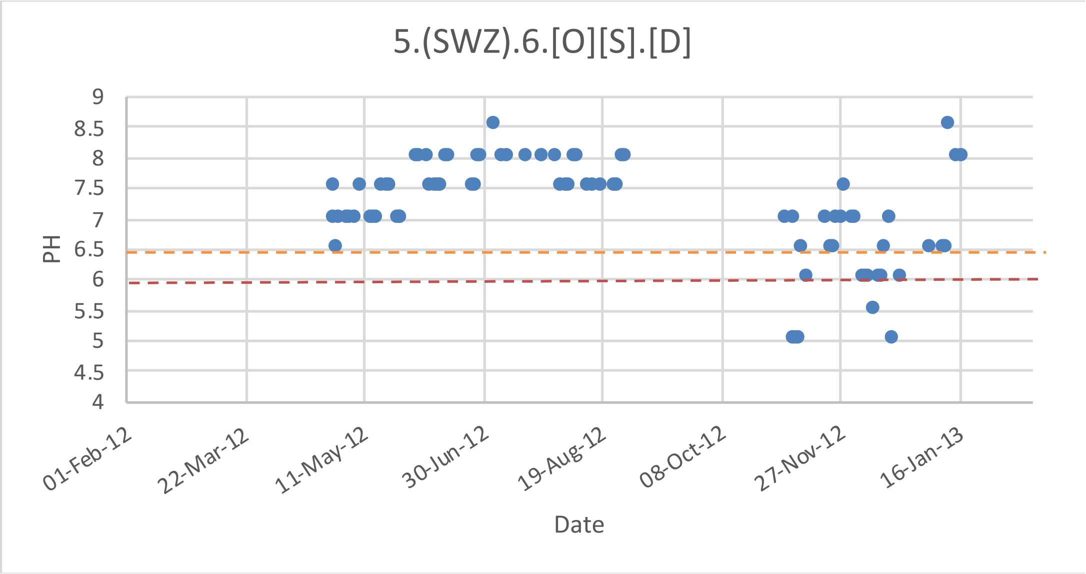


Figure 20. pH vs time series for 5.(SWZ).6.[O][S].[D] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

The first instance of a decline in pH was a switch to dairy as the only organic waste, while the second was a switch to high cellulosic feed substrate, namely grass. Therefore, the first set of data could be regarded as results with OFMSW and the second would be more accurately described as actual experimentation with agricultural waste.

The largest of all installations was 6.(WC).20.[O][S].[I] in the Western Cape. This unit was at a wedding and conference venue just outside the greater Cape Town area. The unit was connected to the raw sewage from one toilet and topped up with food preparation waste from the kitchen as well as restaurant waste after events. The pH vs time profile of this unit is shown in Figure 21. The pH profile shown many instances of decline and recovery.

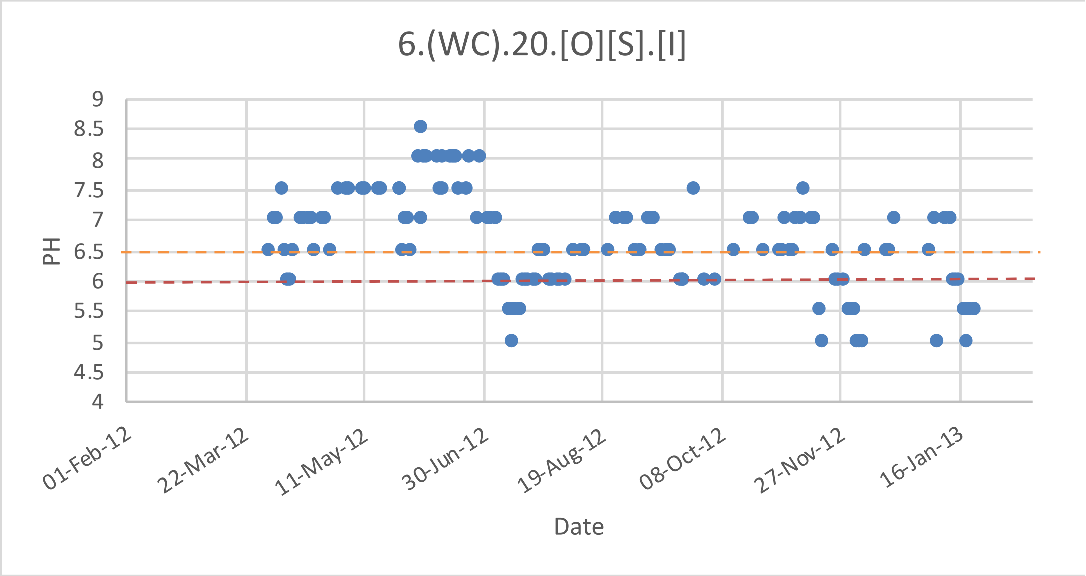


Figure 21. pH vs time series for 6.(WC).20.[O][S].[I] (●) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

Declines in pH were noted after events, i.e. whenever there would have been a sharp increase in the amount of organic waste and also when the amount of raw sewage would probably have increased as well. The time of the highest instability was between November and mid-January, when the venue was full every week, their peak season.

7.(LIM).8.[A][M].[D] was only monitored for 3 months. It was a small-scale unit in the Limpopo province. It was donated as a demonstration unit to show how biogas could be harnessed from manure and agricultural waste. The pH vs time series for this unit is shown in Figure 22.

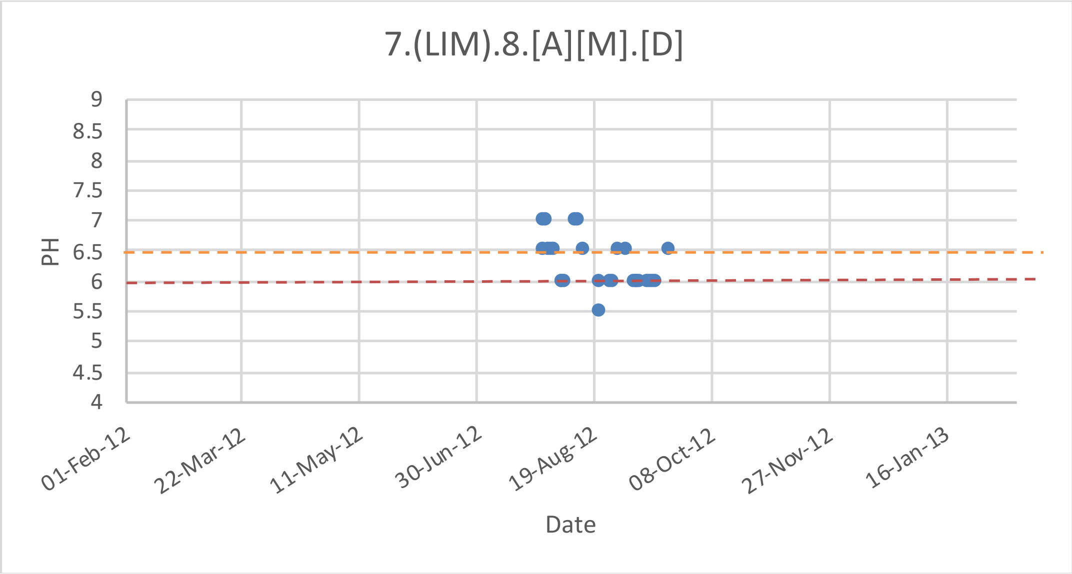


Figure 22. pH vs time series for 7.(LIM).8.[A][M].[D] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

There was only one recording of a pH below 6.0 and the value was 5.5. It is unclear what caused this perturbation as, upon analysis, there was no change in the feeding regime. It is possible, given the error margins in the readings, that this data point was an outlier.

There were two similar installations which used agricultural waste and manure as substrates. 8.(KZN).8.[A][M].[D] and 9.(WC).10.[A][M].[I] were in KwaZulu-Natal and the Western Cape respectively. The pH vs time profiles of these two units are shown in Figure 23 and Figure 24 respectively. 8.(KZN).8.[A][M].[D] was considered domestic as it was a small household next to a farm which bought manure and agricultural waste to feed the digester and was used to cook food for the household. 9.(WC).10.[A][M].[I] was considered institutional as it was located at the large kitchen at a rural school and used to prepare meals for the learners. The more consistent and homogenous feedstocks appear to have shown more stability in the pH trends as there is a smaller range in pH readings in the data sample for both units.

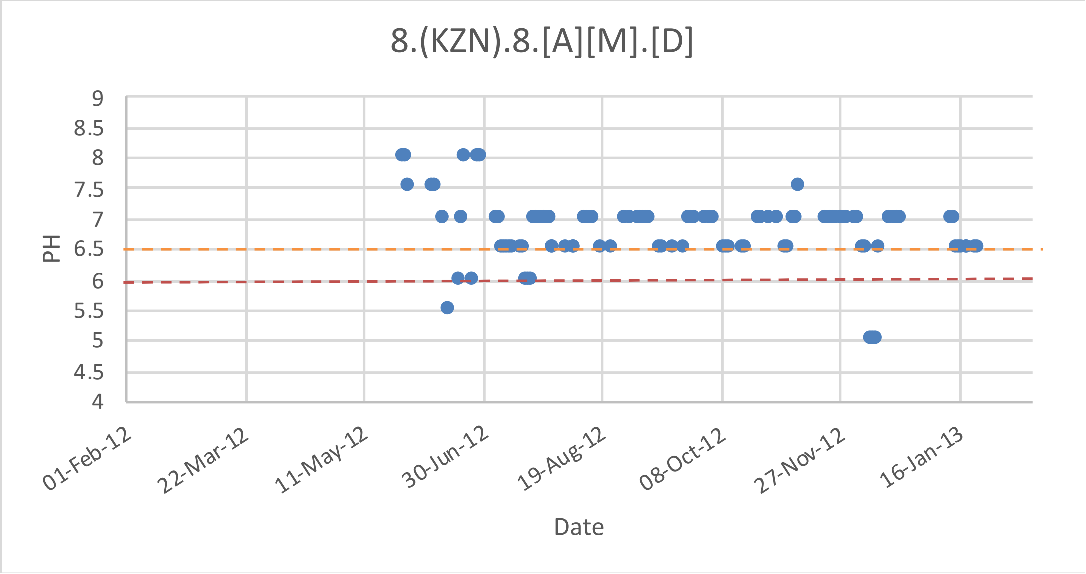


Figure 23. pH vs time series for 8.(KZN).8.[A][M].[D] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

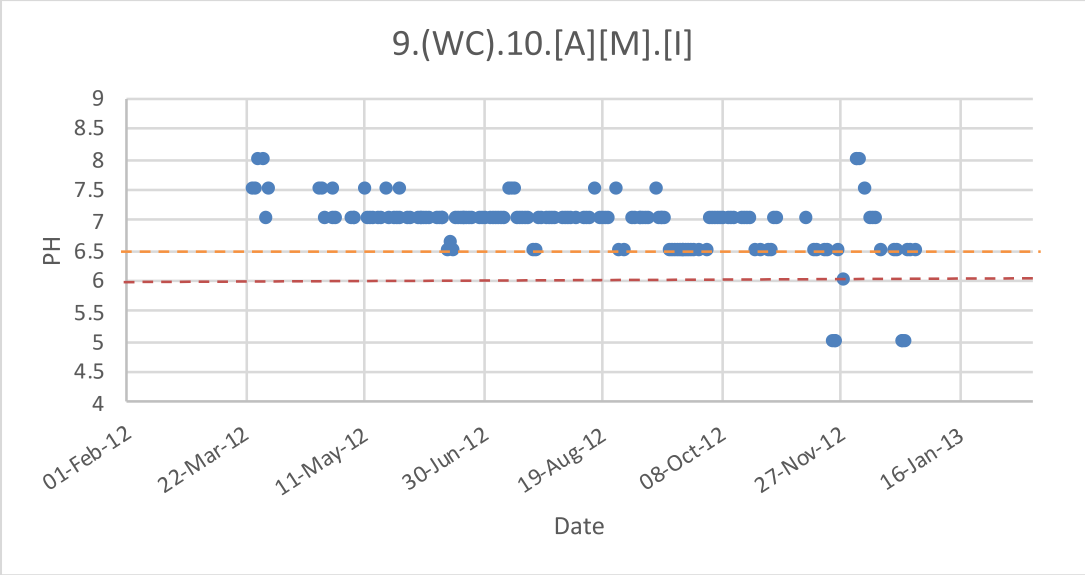


Figure 24. pH vs time series for 9.(WC).10.[A][M].[I] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

There are two instances of a decline in pH each unit. For 8.(KZN).8.[A][M].[D], the first instance was at the very start, when the feeding regime was being fine-tuned, with one more instance in late November 2012. Contact with the operator indicated that while the feedstock had remained the same, there was a change in the ratio between the agricultural waste and the manure at that time.

9.(WC).10.[A][M].[I] showed two instances of a decline in pH, as well as notable fluctuations at the end of 2012 and in early 2013. This unit, as mentioned, was at a school where the normal operator went on leave and handed over to a new operator during this period. The new operator fed the digester and took the readings at the end of the calendar year. It is possible that this contributed to the instability, but it was never confirmed. There was no notable change in the feeding regime.

Lastly, there was one unit which was connected to a sewage outlet, and also fed with animal manure. This was on a farm in the Western Cape. The pH profile for this unit, 10.(WC).6.[M][S].[I] is shown in Figure 25. This unit was largely stable, save for a few instances from October to December 2012.

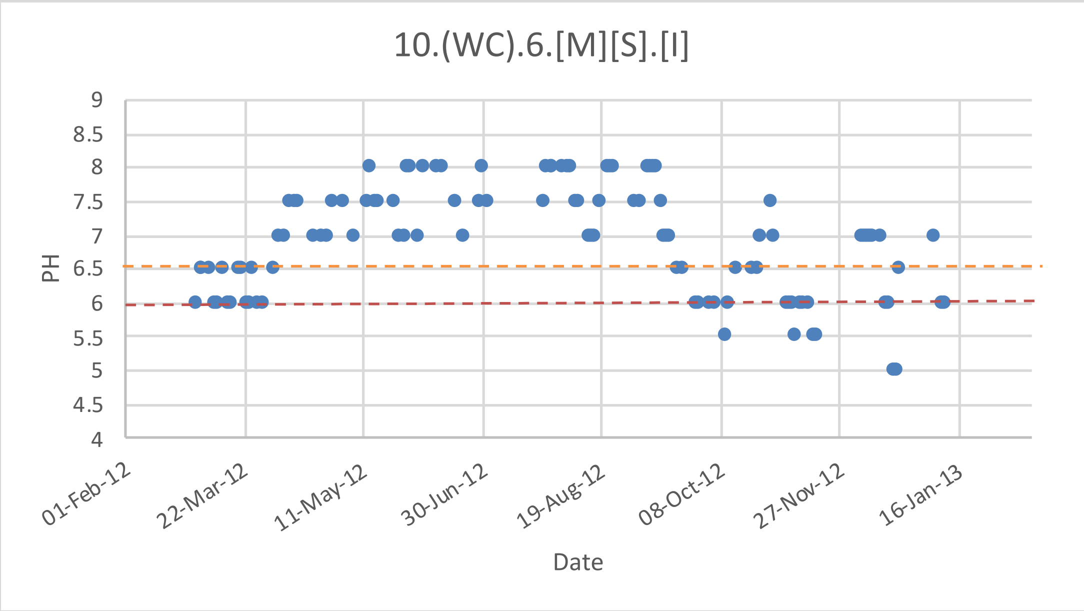


Figure 25. pH vs time series for 10.(WC).6.[M][S].[I] (•) with trendlines marking a pH of 6.5 (- -) and a pH of 6.0 (- -).

For the larger part of the year, the unit was topped up with regular, and consistent amounts of manure. Contact with the user revealed in October, they had changed the manure feeding regime from 3 times per week to once a week. This was very possibly the cause of the instability of the unit.

5.1.1.2. Summary of observations in acidity profiles

The details of the observations are summarised below in Table 13. Two of the readings which were considered outliers, when there was no explainable reason which could be attributed to the decline in pH. These were noted once for 2.(WC).10.[O].[I], and once for 7(LIM).8.[A][M].[D]. While these occurrences were noted below, they were not commented on in Table 13. The reason for the low pH readings for 4.(EC).6.[O][S].[D] were never resolved. In Table 13, the second column refers to the number of readings where the pH was lower than 6.0, while the Episodes refer to the number of times the pH dropped below 6.0 and then recovered. Thus, for 3.(WC).6.[O][S].[D], there were twelve readings below pH 6.0, but they occurred over only five episodes where the biogas unit was unstable and then recovered.

Table 13. Observations of low acidity in all biogas units across remote monitoring study.

Unit	Readings	Episodes	Postulated reason for decline in pH
1.(WC).6.[O].[I]	5	4	Only carbohydrates
2.(WC).10.[O].[I]	3	2	Large amount of only simple carbohydrates
3.(WC).6.[O][S].[D]	8	3	Increase in HH occupancy
4.(EC).6.[O][S].[D]	51	16	-
5.(SWZ).6.[O][S].[D]	5	2	Own experimentation with feedstock
6.(WC).20.[O][S].[I]	18	5	Increase in HH occupancy
7.(LIM).8.[A][M].[D]	1	1	-
8.(KZN).8.[A][M].[D]	4	2	Change in feedstock ratios
9.(WC).10.[A][M].[I]	6	2	Change in operator
10.(WC).6.[M][S].[I]	5	4	Change in frequency of feed

The first observation is that almost every unit in this study experienced incidences of low pH. 7.(LIM).8.[A][M].[D] had only the one instance and it could not be attributed to anything significant, but it was also monitored for the shortest amount of time (three months), so there would likely be other occurrences of low pH if the unit had been monitored longer. Secondly, almost all instances of low pH can be accounted for by a previous change in the feeding regime, either by way of an increase in carbohydrates, an increase in household occupancy (and therefore sewage), or other changes in the feeding regime. Units fed with agricultural waste and manure (more homogenous and consistent feedstocks) seem to show more stability. Finally, it should be noted that the remote monitoring method was able to identify the instances of instability and also, in some cases, since the user was contacted, allowed the user to act quickly to mitigate for it.

5.1.2 The effect of organic loading rate on stability

It has been noted from Chapter 4, and from Section 5.1.1 that the feeding regime had an impact on the acidity level of the digester. In some instances, this was attributed to a change in the feeding regime, often an increase in one of the feedstocks. Therefore, a comparison was plotted between the average weekly pH against the weekly organic loading rate as calculated in Section 4.4. As 4.(EC).6.[O][S].[D] was shown to be consistently unstable and 7.(LIM).8.[A][M].[D] had only one episode of instability which could not be accounted for, these two units were excluded from the plot. It was difficult to glean anything meaningful from the plot, so the average weekly pH of the subsequent week was then plotted against the organic loading rate of a preceding week and the resulting plot is shown in Figure 26. The reason for that the effects of the feedstock would not be seen on the same day, but rather only in a week would be due to the hydraulic residence time. While appreciative of the fact that these readings are still weekly averages, there does appear to be an indication that there is an observed decline in average pH of most biogas units when the organic loading rate approaches 2.5 $kg.m^{-3}.day^{-1}$. Goux *et al.* (Goux *et al.*, 2015) in their laboratory study noted acidosis (expressed by a decline in pH) starting to occur when the organic loading rate approached 3.0 $kg.m^{-3}.day^{-1}$, noting that the optimum organic loading rate is a function of temperature as well as the nature of the feed (Fang, 2010).

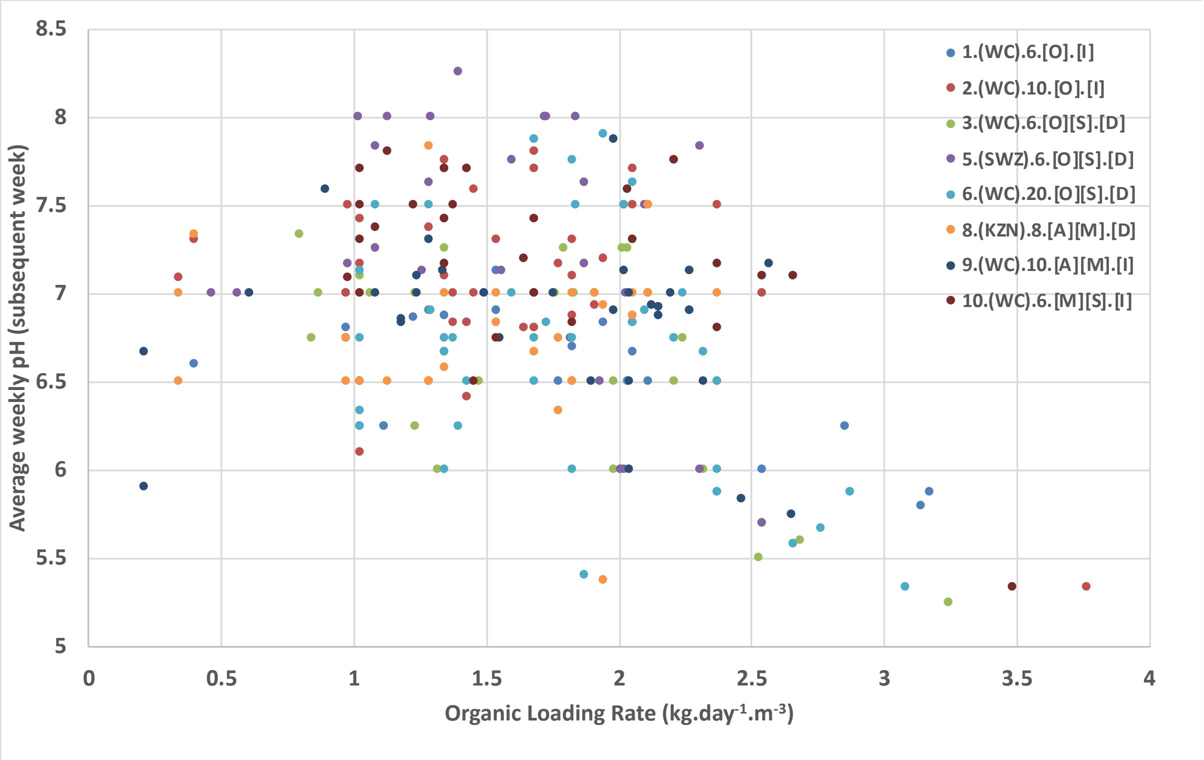


Figure 26. Average weekly pH vs weekly OLR for 1.(WC).6.[O].[I] (●); 2.(WC).10.[O].[I] (●); 3.(WC).6.[O][S].[D] (●); 5.(SWZ).6.[O][S].[D] (●); 6.(WC).20.[O][S].[D] (●); 8.(KZN).8.[A][M].[D] (●); 9.(WC).10.[A][M].[I] (●) and 10.(WC).6.[M][S].[I] (●).

There are some exceptions to this, with 9 having a reading of just below 6.0 at a very low organic loading rate. As mentioned in Section 5.1, the instability of this unit was attributed to a change in operator and is therefore a notable outlier. Units 6.(WC).20.[O][S].[D] and 8.(KZN)8.[A][M].[D] each showed an episode where the average pH for the week was low despite an organic loading rate below 2.0 kg.day^{-1}.m^{-3}. For the former, the decline in pH was Episode 5 depicted in Figure 30, where there was also no reduction in burning time post the low pH episode, nor was there a notable change in gas quality. It is possible that this in fact was not a low pH event but rather a misread. For the latter, the decline in pH was attributed to a change in the feedstock ratios, not the quantities, so it holds that the pH would decline in a subsequent week, despite no change in the organic loading rate. There are nineteen organic loading rate readings above 2.5 kg.m^{-3}.day^{-1} of which thirteen have an average pH of below 6.0 in the subsequent week. Thus, it should be noted that it is not only the type of food fed in the feeding regime, but also the quantity and volume which can lead to episodes of instability.

5.2 The effect of instability on biogas production/utilisation

The important impact to the user would be whether or not the incidence of low acidity affected their gas production, either by the quantity or the quality of gas produced. Again, notes made that the burning time was an indication of gas used, rather than the gas produced. Still, the time series is plotted a week before and a week after the incidence of low pH. For 1.(WC).6.[O].[I], this occurred 4 times, and the burning time series is plotted against this series, with day 0, as the first day of low pH and the start of the episode, shown in Figure 27. The total burning time of the stove is seen to decline in all episodes in days following a low pH reading. Further investigation into reported data, shows that in three of the four cases, there was also a note from the user that the flame quality had been compromised, a change in reading from "Blue" to "Yellow(unstable)". These three episodes of poor flame quality were around the incidences of low pH and also the only instances of poor flame quality reported in the data set.

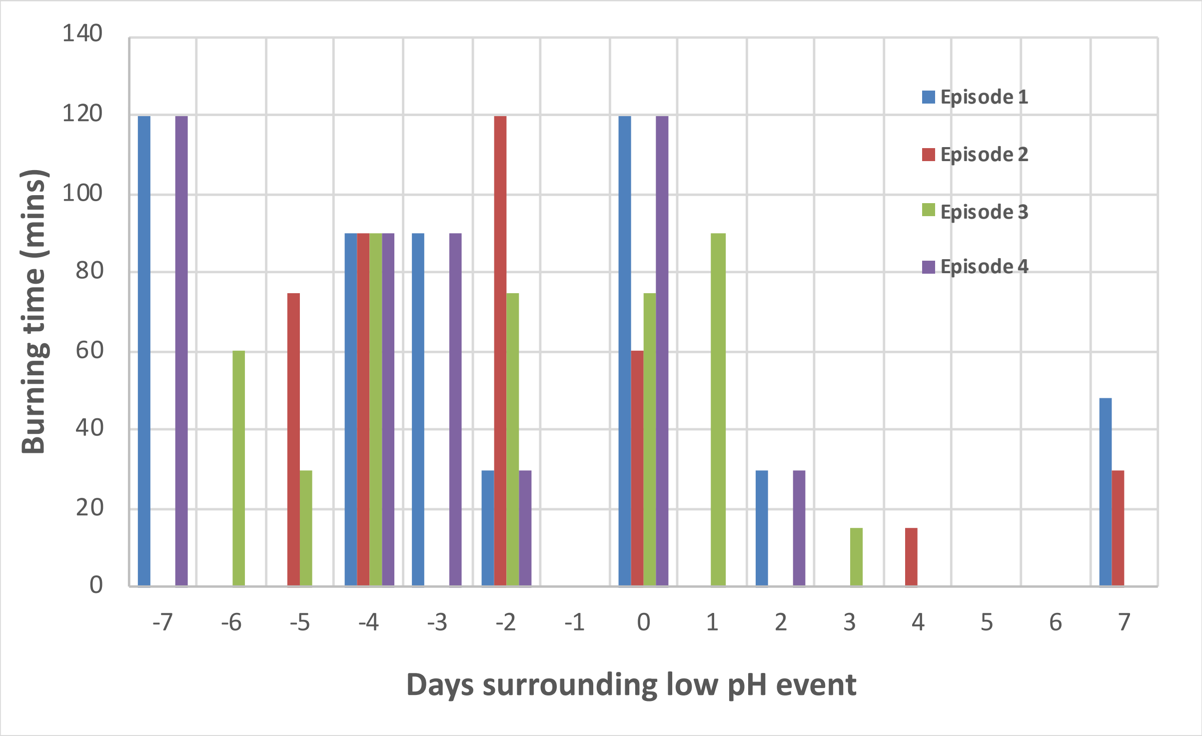


Figure 27. Burning times around episodes of low pH for 1.(WC).6.[O].[I].

This analysis was repeated for the other units, with the noted exclusions of 4.(EC).6.[O][S].[D], and 7.(LIM).8.[A][M].[D] as the former was consistently unstable, while no reason for the one instability could be attributed to the latter (and the reading was disregarded). 5.(SWZ).6.[O][S].[D], 8.(KZN).8.[A][M].[D] and 10.(WC).6.[M][S].[I] reported no variation in burning time, in that they consistently reported the same burning time daily over the period of instability. 5.(SWZ).6.[O][S].[D] and 8.(KZN).8.[A][M].[D] reported unchanged burning times of 60 minutes and 90 minutes respectively, while 10.(WC).6.[M][S].[I] reported a burning time of 240 mins consistently over the periods of instability. That left 2.(WC).10.[O].[I], 3.(WC).6.[O][S].[D], 6.(WC).20.[O][S].[I] and 9.(WC).10.[A][M].[I] to undertake the investigation on. These plots are shown in Figure 28, Figure 29, Figure 30, and Figure 31 respectively.

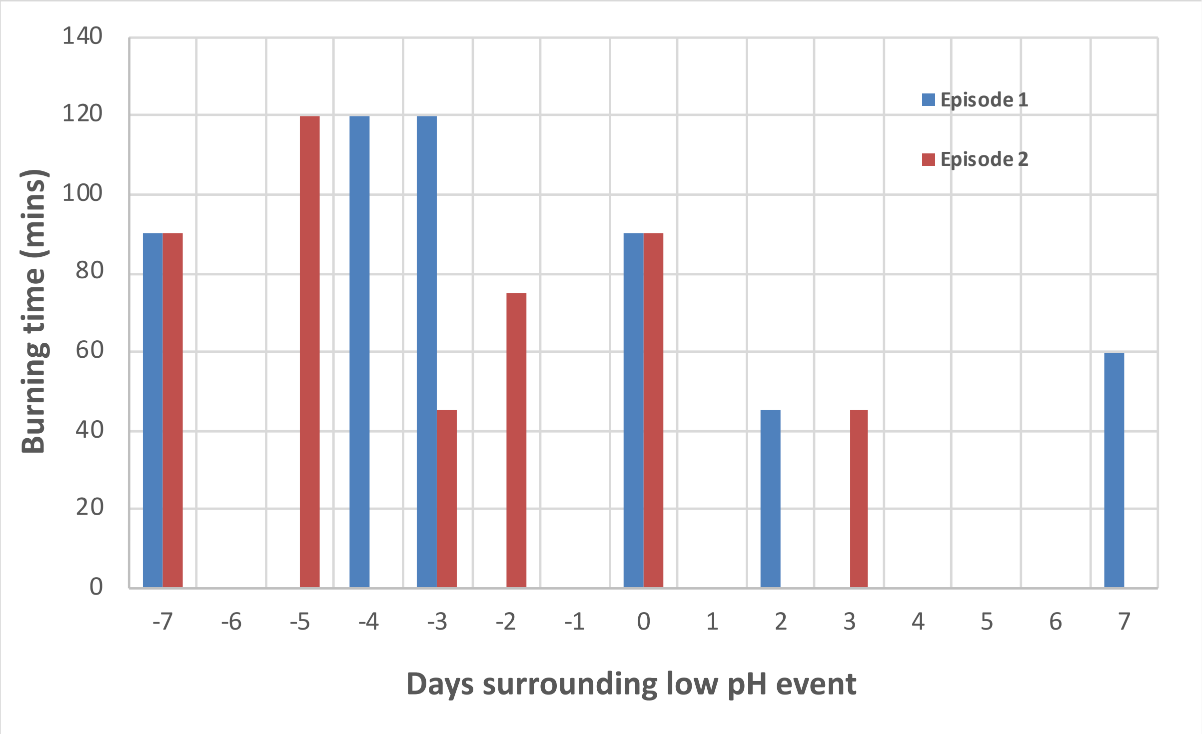


Figure 28. Burning times around episodes of low pH for 2.(WC).10.[O].[I].

For the days following the incidences of low pH readings in 2.(WC).10.[O].[I], shown in Figure 28, the same trend of reduced burning time was noted. Further investigation again revealed reports of poor flame quality for this biogas unit after the incidence of low pH. The total burning time in the days after the low pH event is less than 20% of the total burning time leading up to and on the day of the low pH event.

For 3.(WC).6.[O][S].[D], shown in Figure 29, a similar result is observed for Episodes 1 and 3, where the burning time after the event of low pH is under 30% of the days preceding the event. For Episode 2, there is a reduction in utilisation, but only by 25%.

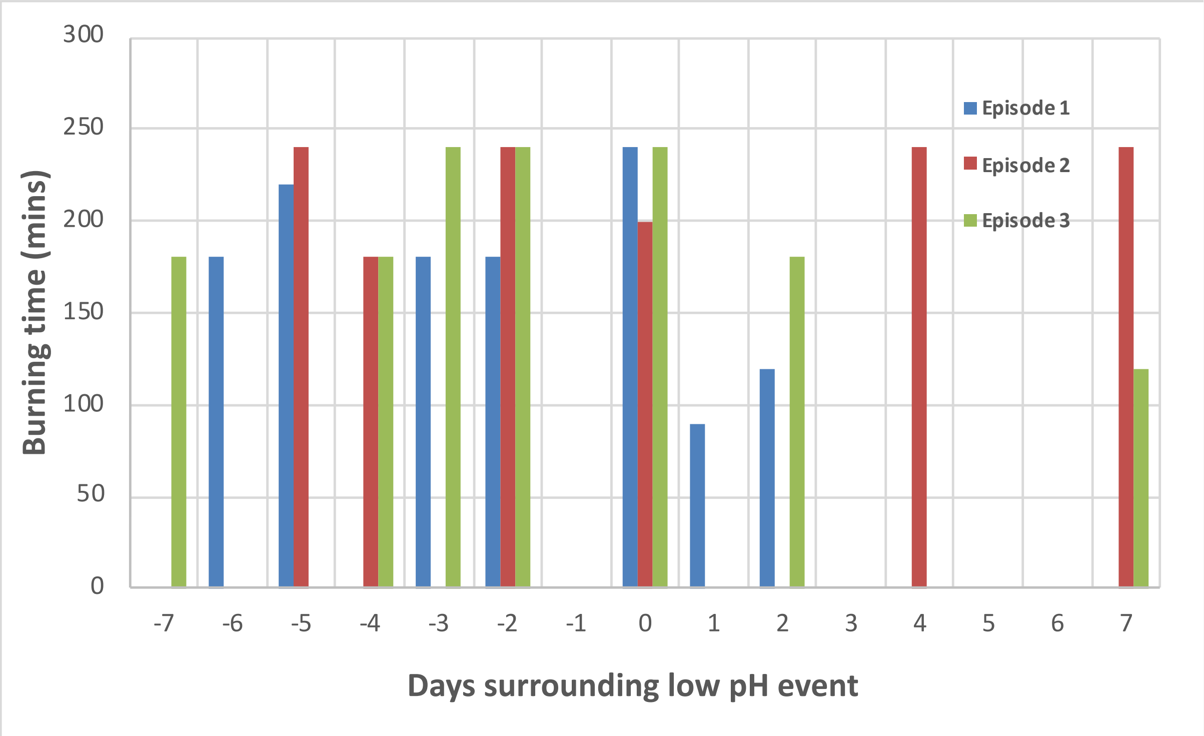


Figure 29. Burning times around episodes of low pH for 3.(WC).6.[O][S].[D].

For 3.(WC).6.[O][S].[D], unlike the first two biogas units, the episodes of low pH were attributed to an increase in household occupancy, rather than a large amount of simple carbohydrates. Referring back to Figure 18, it should be noted that both Episodes 1 and 3 lasted for over 5 days, while Episode 2 was only 3 days long. This may explain why the utilisation was higher in this episode than the other two, possibly due to a shorter episode length.

Figure 30 shows the same analysis for 6.(WC).20.[O][S].[I], illustrating that the first 4 episodes shows a decrease in total burning time to between 35% and 56% of the burning time before the pH incident. Further analysis reported that there was poor flame quality reported in Episodes 2 and 4. For Episode 5, there was no change in the total burning time before and after the episode and also no reported change in flame quality (as for Episodes 1 and 3).

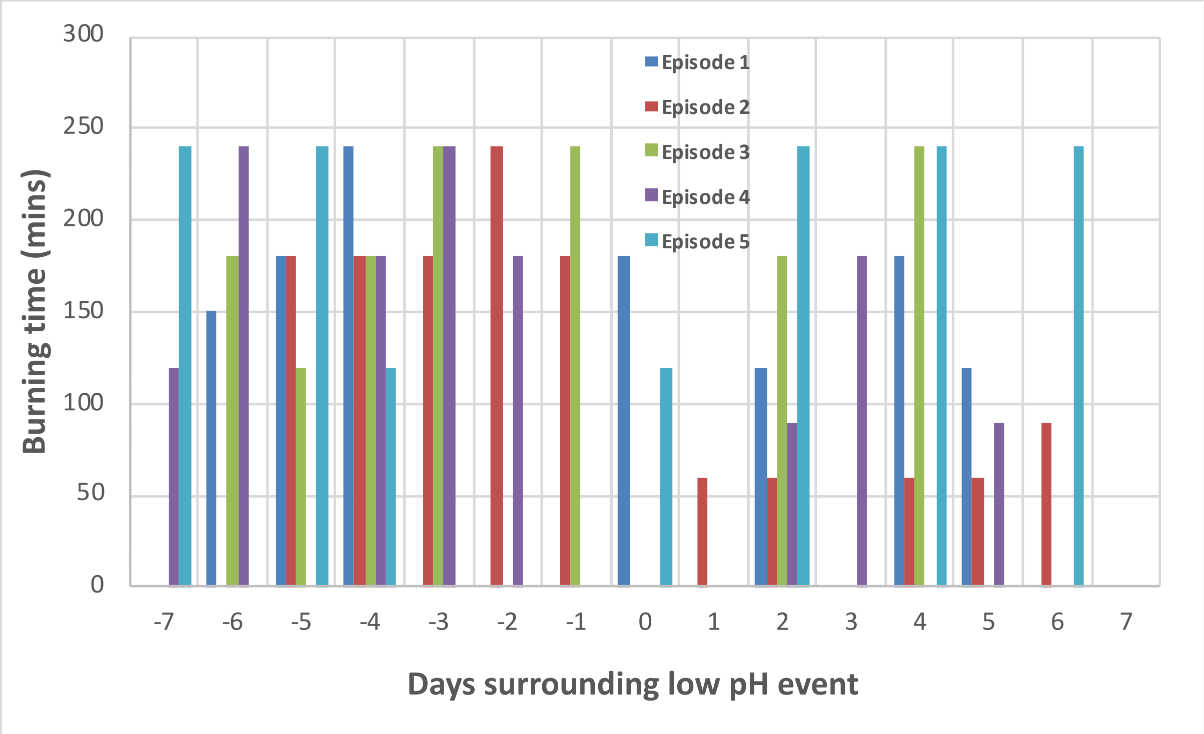


Figure 30. Burning times around episodes of low pH for 6.(WC).20.[O][S].[I].

Finally, the analysis is shown for 9.(WC).10.[A][M].[I] in Figure 31. There were two episodes. The burning time in days following the low pH event averaged 30% of the burning time of the week before. Both incidences also reported a change in flame quality.

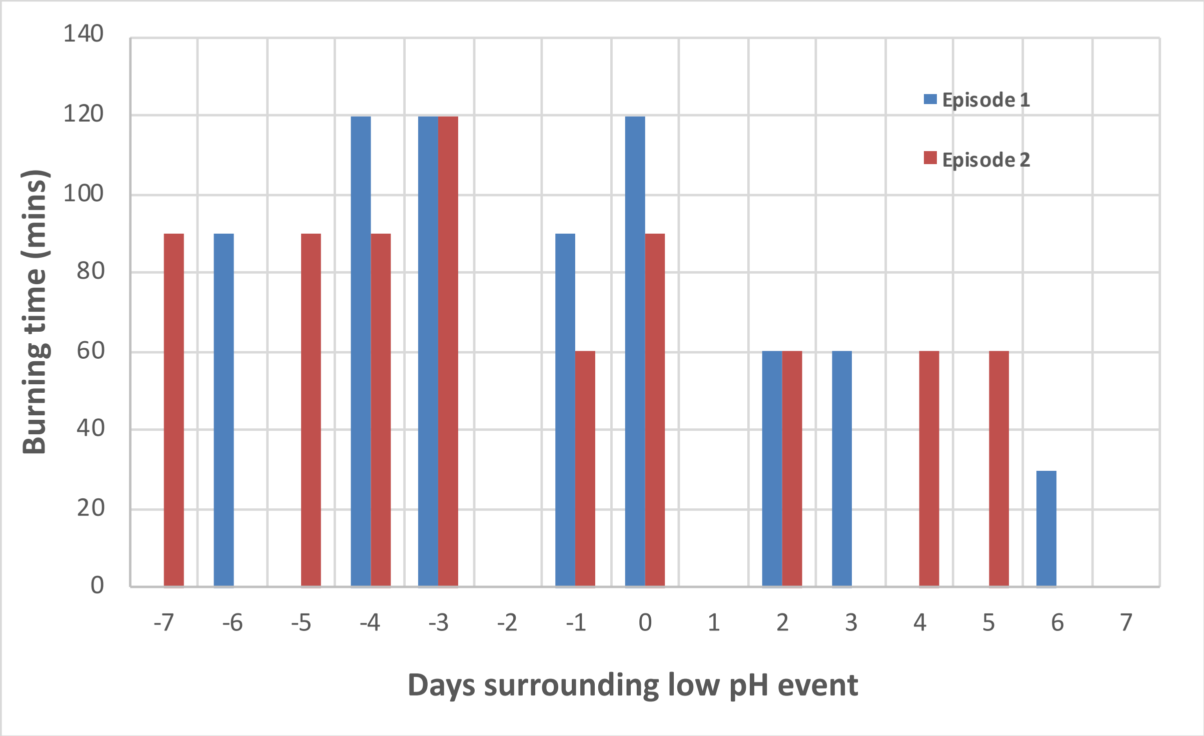


Figure 31. Burning times around episodes of low pH for 9.(WC).10.[A][M].[I].

To summarise, two units were excluded from this analysis as one had only one reading which was deemed to be in error while the other was constantly unstable. Of the eight units which remained, three were unaffected by way of burning time or flame quality. Of the five remaining units on which this analysis was undertaken, there were sixteen episodes of low pH in which fourteen of those episodes showed a reduction in the cumulative burning time in the week of the low pH episode compared to the previous week. In eight of these fourteen episodes, there was a further note that the flame quality (an indication of gas quality) has changed from stable (blue) to unstable (yellow). Although the burning time is not a direct indication of the productivity, there is certainly an effect of stability on the gas utilisation and on the flame quality.

5.3 Productivity of Biogas units

The approach here was to use the biogas utilisation as an indication of productivity in order to inform Hypothesis 2. As previously mentioned in Section 5.2, the gas utilisation was implemented as an indication of the gas used, rather than the gas actually produced. The approach taken here was different to the approach previously taken for the stability analyses in the previous section. In the previous section, each instance of instability was analysed, a summary was generated and discussions around trends were used to inform insights. In this case, it was first necessary to determine which units were unstable so that periods of instability could be left out of the analysis. Secondly, an overall picture was analysed and then singular effects, such as the effect of climate and feedstock were inspected in more detail. While different to the previous section, the nature of the analysis necessitates a change in approach.

5.3.1 Gas utilisation of the biogas units

Average gas utilisations were calculated across the twelve-month period and are displayed in Table 14 in decreasing order. Five of the top six places are for institutional rather than domestic installations and are highlighted below. It was checked whether either of the highest utilisations, i.e. 10(WC).6.[M][S].[I] and 6.(WC).20.[O].[I], ever reported running out of biogas, and there was never a report as such. The table further includes (column 3) the number on readings when the unit was unstable and what these readings were as a percentage of the total readings. Lastly, the average annual temperature sourced from AccuWeather (AccuWeather, 2012) is included in column 4 as an indication of what effect the climate may have had on the unit in order to inform Hypothesis 2.

Table 14. Average gas utilisation of the remote monitoring users from Feb 2012 to Jan 2013

Unit	Average utilisation efficiency	Instability Readings(%total)	Average daytime temperature
10.(WC).6.[M][S].[I]	48%	5(6%)	23 °C
6.(WC).20.[O][S].[I]	42%	18(13%)	23 °C
2.(WC).10.[O].[I]	32%	3(2%)	23 °C
8.(KZN).8.[A][M].[D]	30%	4(4%)	26 °C
1.(WC).6.[O].[I]	28%	5(5%)	23 °C
9.(WC).10.[A][M].[I]	24%	6(4%)	23 °C
3.(WC).6.[O][S].[D]	23%	8(9%)	22 °C
5.(SWZ).6.[O][S].[D]	19%	5(6%)	19 °C
7.(LIM).8.[A][M].[D]	19%	1(4%)	23 °C
4.[EC].6.[O][S].[D]	18%	51(44%)	20 °C

The two units which are best utilised are those which operate on sewage and OFMSW. However, this does not necessarily speak towards the quality of the feedstock. More interestingly, 6.(WC).20.[O].[I] is located at a guesthouse while 10.(WC).6.[M][S].[I] is at a school. 2.(WC).10.[O].[I] was at a community centre. In all cases, gas was used for meal preparation. The higher utilisation would indicate that the users will use the gas which they need, rather than the total gas available. Whether or not this was indeed the case, the hydraulic residence time would need to be considered. If the hydraulic residence time was high, then indeed, almost all the substrate would be converted to biogas and the calculated utilisations would be correct. However, if the hydraulic residence time was low, then not all the substrate may have been converted to gas, and the utilisation may in fact be higher. For example, in 6.(WC).20.[O][S].[I], where the unit was connected to the sewage outlet. When there was an increase in occupancy, the hydraulic residence time would have decreased with the increasing water being flushed through, meaning that the utilisation calculated may in fact be higher. This is noted as a further limitation of the methodology used to investigate Hypothesis 2, which is around productivity of small-scale biogas units.

5.3.2 Normalised gas use by month

The normalised burning time was calculated and converted to normalised gas use per month calculated from Section 4.4.1 and shown by month in Figure 32, with the average annual gas utilisations for the same units taken from Table 14 plotted against a secondary y-axis. Based on the gas utilisation calculation, it could be seen that even 10.(WC).6.[M][S].[I] which is the unit with the highest normalised gas use, still has an average gas utilisation of less than 50%. The graph naturally only depicts average monthly normalised burning times for the months where there was data, e.g. 7.(LIM).8.[A][M].[D], where data was only captured over three months, there are only three records for July, August and September.

The first observation was around the gas utilisation, where calculations appeared to show that it was possible that all the gas produced was not used, and further, that it is possible that the units are also not being fed a maximum design capacity. The reason why these observations were not firm, is due to notes from previous discussions that utilisation were not a definitive indication of productivity, and the limitations in calculation of full gas utilisations. However, the first theory stating that not all the gas produced was used, was supported by the fact that no units ever reported running out of gas. The impact on gas production was further explored under the headings of feedstock and climate in Sections 5.3.3 and 5.3.4.

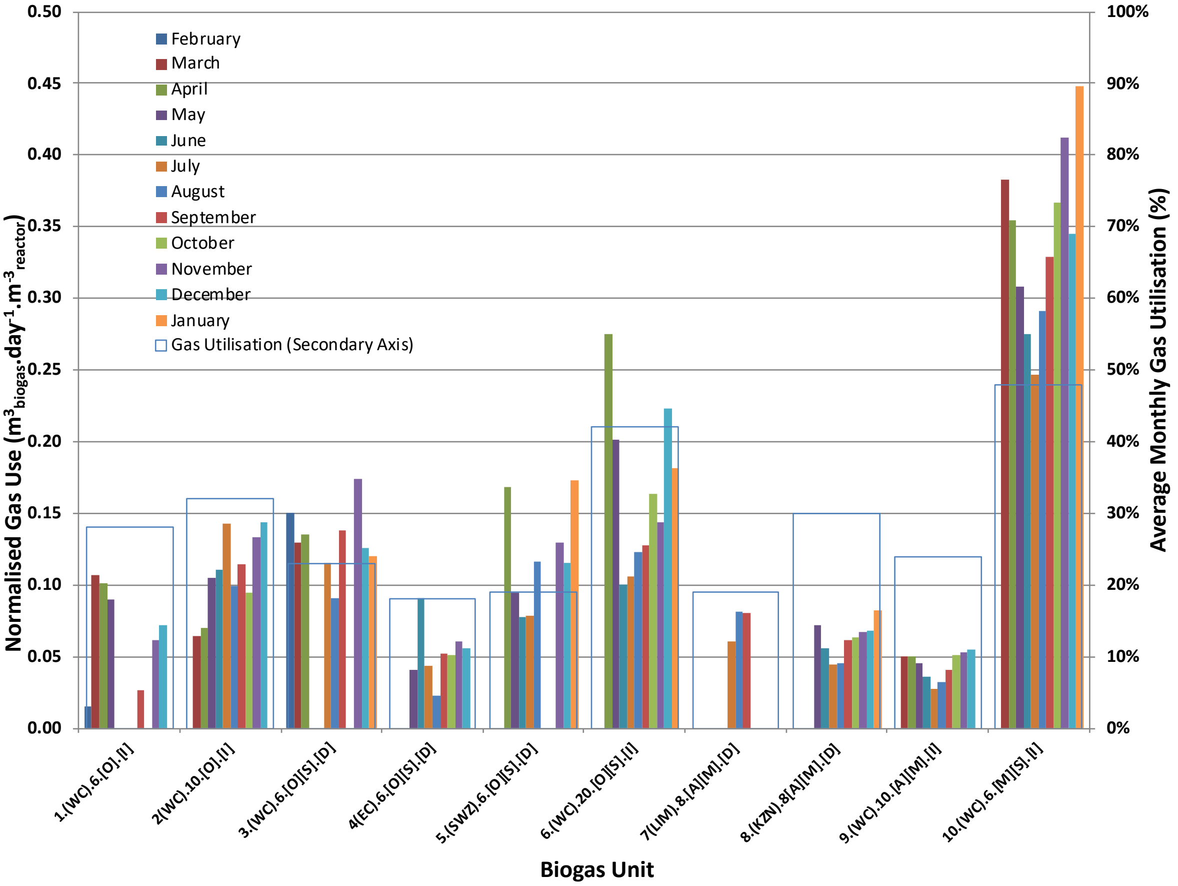


Figure 32. Average daily normalised gas use by month (primary axis) and average annual gas utilisation (secondary axis) for all units over Phase 2, from February 2012 to January 2013.

The second observation was that there appears to be a seasonality in the biogas utilisation. Of the ten units observed, six of them had data ranges over the winter months of June and July. These were units:

- 2.(WC).10.[O].[I]
- 4.(EC).6.[O][S].[D]
- 5.(SWZ).6.[O][S].[D]
- 8.(KZN).8.[A][M].[D]
- 9.(WC).10.[A][M].[I] and
- 10.(WC).6.[M][S].[I]

All the above units, except for 5.(SWZ).6.[O][S].[D] showed a decrease in normalised monthly gas use after May followed by an increase after August, giving a strong indication of seasonality (through ambient temperature) being linked to gas usage.

5.3.3 The effect of feedstock on productivity

The following four units were chosen for the investigation of the effect of feedstock on productivity:

- 1.(WC).6.[O].[I] - feedstock OFMSW
- 6.(WC).20.[O][S].[I] - feedstock OFMSW and sewage
- 9.(WC).10.[A][M].[I] - feedstock agricultural waste and manure
- 10.(WC).6.[M][S].[I] - feedstock manure and sewage

While there is a difference in size of the biogas units, all units were based in the Western Cape, all are at institutions and therefore have the same stove, and it is only the feedstock which varies between them. Firstly, reflecting back to Table 14, it is observed that all these units shown, are in the higher gas utilisation, which has been attributed to the demand for gas at an institutional level more than anything else. Notably, 6.(WC).20.[O][S].[I], is second highest on gas utilisation, but also second highest in readings and % of instability. This would imply that a biogas unit can be unstable, but also productive.

Normalised gas use shows the best use being for 10.(WC).6.[M][S].[I] which has manure and sewage, followed by 6.(WC).20.[O][S].[I] being OFMSW and sewage, followed by 1.(WC).6.[O].[I] and finally 9.(WC).10.[A][M].[I]. This would imply that having the sewage outlet connected to the biogas unit is beneficial for gas utilisation, possible since the feedstock (human sewage) is more readily degradable. In this case, the members of the household would essentially have been pre-treating the feedstock.

5.3.4 The effect of climate on productivity

The first comparison undertaken to investigate the effect of climate is on the following units which all have OFMSW and sewage as the feed, but are based in different climates:

- 3.(WC).6.[O][S].[D] - based in the Western Cape, daytime mean of 22 °C
- 4.(EC).6.[O][S].[D] - based in the Eastern Cape, daytime mean of 20 °C
- 5.(SWZ).6.[O][S].[D] - based in Swaziland, daytime mean of 19 °C
- 6.(WC).20.[O][S].[I] - based in the Western Cape, daytime mean of 23 °C

In this case, 4.(EC).6.[O][S].[D] was excluded from the data set as it was plagued with instability. The two units in the Western Cape were in different parts of the Western Cape, hence the difference in reported temperature. However, these units, 3.(WC).6.[O][S].[D] and 6.(WC).20.[O][S].[I], showed similar normalised gas use, typically ranging between 0.1 and 0.2 $m^3_{biogas}.day^{-1}.m^{-3}_{reactor}$. Between them, 6.(WC).20.[O][S].[I] showed a higher gas utilisation, explained by the fact that it was at an institutional level. Comparing these two to the unit in Swaziland which was at a lower temperature, there was no observable difference between its performance by way of the gas utilisation, nor the normalised gas use.

The second comparison undertaken to investigate the effect of climate is on the following units which all have agricultural waste and manure as the feedstock, but are based in different climates:

- 7.(LIM).8.[A][M].[D] - based in the Limpopo Province, daytime mean of 23 °C
- 8.(KZN).8.[A][M].[D] - based in Kwa-Zulu Natal, daytime mean of 26 °C
- 9.(WC).10.[A][M].[I] - based in the Western Cape, daytime mean of 23 °C

Limited data was available for the unit in Limpopo as it was only monitored for three months. The unit in KwaZulu-Natal displayed a higher normalised gas use than the unit in the cooler climate, in the Western Cape, 0.06 vs 0.04 $m^3_{biogas}.day^{-1}.m^{-3}_{reactor}$, with only a slightly higher gas utilisation 30% vs 24%. Again, no conclusive impact of climate can be drawn from this, other than that it appears that temperature may possibly have an effect on productivity.

5.4 Summary of findings and conclusions

From this study, it was established that the smart monitoring via smartphone app with very basic measurement of parameters was able to provide some insight into the operations of small-scale biogas units. The pH detection system via the website provided enough information to detect an instability and in cases, contact the operator and make correction for it. The corrections made were the addition of lime (if available) or a brief cessation in feed. Both techniques were learned from the observational study in Chapter 4. The flame quality selection was also able to provide insights into the gas quality.

The heterogeneity of food waste appears to be responsible for the instability observed by pH readings. Moreover, upon further investigations, it is the addition of simple carbohydrates which appears to cause a decrease in pH for units which have OFMSW in the feedstock. In other cases, it was an increase in the household members which lead to an increase in organic loading rate which was attributed to be responsible for the instability. Finally, a change in the frequency and ratios is also seen to have an effect on stability. In five of the ten units, there was no reported effect of low pH on gas production or quality. In the other five, there were sixteen episodes of a low pH, of which fourteen of those episodes showed a reduction in the cumulative burning time in the week of the low pH episode, compared to the week before. In eight of these fourteen episodes, there was a further note that the flame quality (an indication of gas quality) had changed from stable (blue) to unstable (yellow). These are important findings when considering small-scale biogas for urban Africa, where the feedstock will be predominantly OFMSW. If small-scale biogas is being utilised to meet primary energy needs, low gas quality may have drastic impacts on the success of the technology. Hypothesis 1 is addressed here as the feeding regime and in particular, the effect of simple carbohydrates is noted.

While it is postulated that the climate or ambient temperature would have an effect on gas production, it appears that the type of installation is more significant than the climate. For example, on the whole, units installed at institutions displayed higher gas utilisations than domestic ones. That being said, some seasonality is still observed in five of the six units which were monitored over winter months. As there were limitations in the sampling method, as well as in the ability to measure some of the parameters, much of the analysis on productivity was inconclusive and warrants further investigation to more confidently make the link between temperature and productivity and to fully address Hypothesis 2.

Reflecting on remote monitoring, it has been shown that the tool was able to detect instances of instability and even able to detect changes in gas quality as such times. The tool was unable to predict future instability, but by contact with the users, it was valuable in correcting incidences of instability. Therefore, in light of Hypothesis 3, remote monitoring has proved useful, supporting the effective operation of biogas units. However, there are some limitations to what it can monitor and infer notably, that it also relies on a person checking the data frequently and engaging with the biogas operator.

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Chapter 6: Field Experimentation

After the conclusion of the remote monitoring study, and given the emerging observations on productivity and stability, particularly around organic waste, there emerged further theories around organic waste and unvalidated techniques for mitigation against instability. From Chapter 5, it was observed that the feeding regime did affect the stability of the biogas unit. Of the three factors (high amount of simple carbohydrate, increases in the organic loading rate and changes in feed ratio/frequency), it was surmised that there may be ways to mitigate for some of these factors (particularly the simple carbohydrates). In 2014, the opportunity arose to conduct experiments on another small-scale biogas unit places at a local composting facility (LCF). Experiments were conducted as described in Section 4.3.3 to advance the understandings of operational stability and productivity, of a biogas unit with a feedstock of OFMSW and further address Hypotheses 1 and 2. Monitoring of this unit was with the now established remote monitoring method using the mobile phone application and pH indicator strip. Instead of taking passive readings, there was a daily active involvement with the biogas unit operator via the mobile phone to further inform Hypothesis 3.

Unlike the UCT biogas unit in Chapter 4, or the remote monitoring biogas units in Chapter 5, the feedstock for the LCF unit was fed a pre-determined regime as described in Section 4.3.3. Initially, there was a stepwise introduction to organic waste from the initial inoculum of cow manure. Then an experiment was done with waste pre-treated with Bokashi. Bokashi treatment involves the layering of organic waste with Bokashi bran followed by a fourteen-day fermentation in an airtight drum. This pre-treated organic waste is then fed to the biogas unit. Finally, there was purposeful introduction of simple carbohydrates in pre-determined quantities. Monitoring was also more active, with daily checking of the data sent through and interaction with the operation via the mobile phone on which the Biogas Monitoring Tool application was loaded.

6.1 Performance on structured feeding regime

The results presented here are for the first part of the study, where the biogas unit was inoculated with cow manure, and then slowly migrated to OFMSW, through the introduction of increasing amounts of source separated food waste.

6.1.1 Migration to OFMSW from manure

OFMSW which was source separated from a nearby mall was introduced in a stepwise function as described in Section 4.3.3. The overall masses of OFMSW fed to the unit are depicted in Figure 33. The mass of OFMSW is shown to increase steadily until mid-July, at which point, less waste was added more frequently until 20 kg was being fed to the biogas unit per day. Thereafter, one 120 dm^3 wheelie filled with OFMSW was fed to the digester per day.

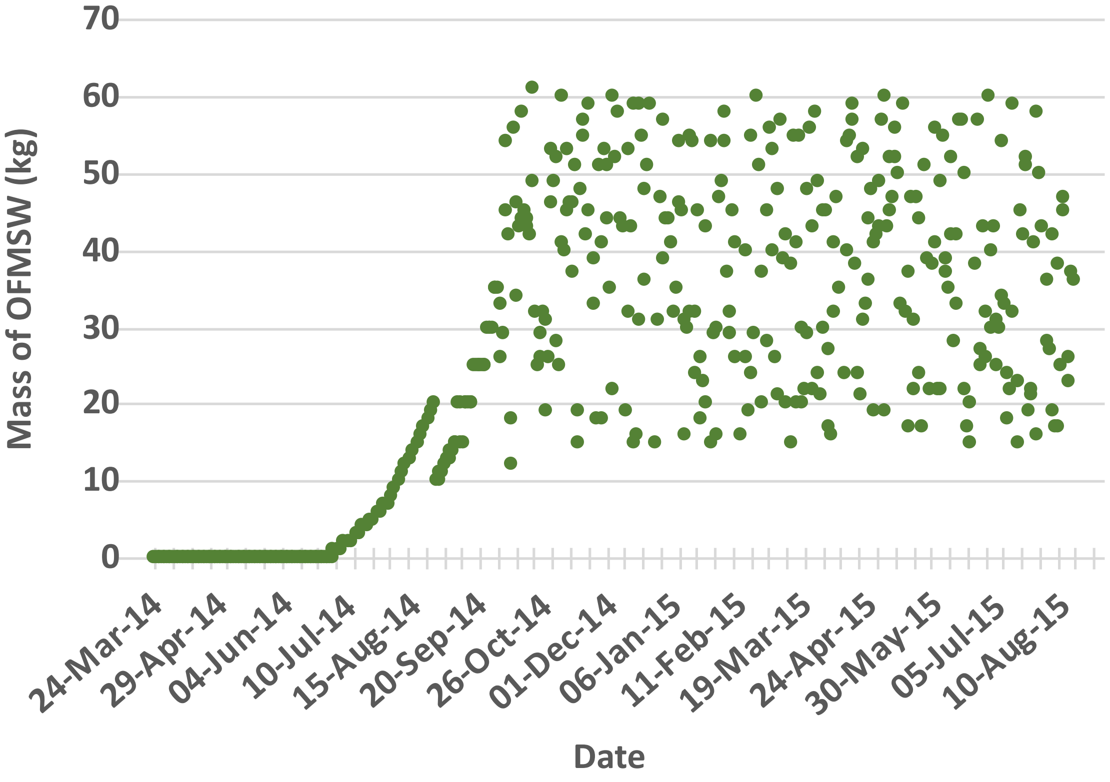

Figure 33. Mass of OFMSW (●) fed to the LCF unit from Mar 2014 to Aug 2015.

Over the entire process, there were fifteen instances when the pH dropped below 6.0 and these were corrected for by the addition of lime as it was for the UCT biogas unit. A summary of the incidences of low pH and the total mass of lime added over the initial phase is presented in Table 15.

Table 15. Frequency of lime treatments in different period of operation of the LCF biogas unit.

	Apr-Jun 2014	**Jul-Sep 2014**	**Oct-Dec 2014**	**Jan-Mar 2015**	**Apr-Jun 2015**	**Jul-Sep 2015**
Number of treatments	2	3	2	4	4	2
Total Mass Added (kg)	8.5	6.5	5.0	7.5	8.5	6.5

Incidences of low pH were picked up on the day. The feeding regime was not altered as it had already been pre-determined, so a weighed amount of lime was added to biogas unit and the unit was agitated with a modified impeller. In this way, the instability was mitigated for with stability returning in 24 to 48 hours.

6.1.2 Gas utilisation

The remote monitoring work in Chapter 5 indicated that ambient temperature may have an effect on productivity of the unit. The results were not conclusive as unverified as the measurements recorded were for the gas used, and not necessarily the gas produced. In this study, the gas was burned to completion every day and the total burning time was recorded. Therefore, in this case, the gas used was the total gas produced. The burning time was converted to a normalised burning time Equation 2 in Section 4.4.1. From here, the normalised gas use using the gas flow rate of the stove as it was for all the remote monitoring units using Equations 10, 11 and 12 from Section 4.4.2. This was done using weekly totals and the results are shown below in Figure 34 along with the daily mean temperatures.

As there was no OFMSW fed to the unit for the first three months, and that cow manure supplemented the organic waste between June 2014 and August 2014, normalised gas use for the first six months of operation were not calculated.

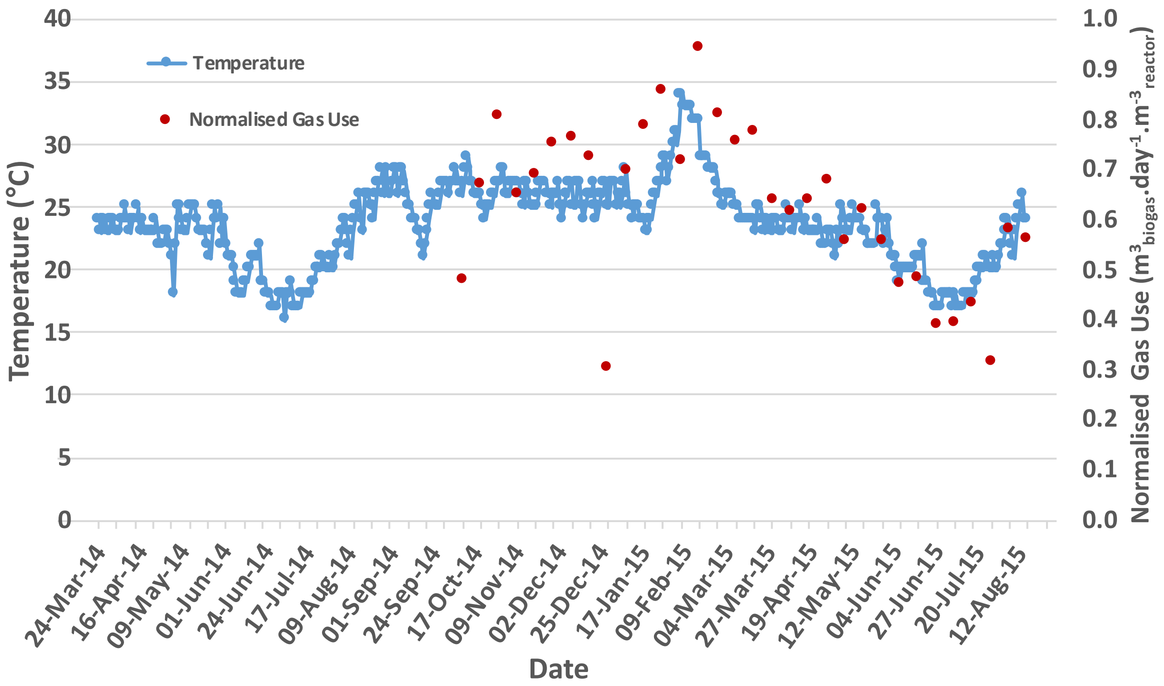

Figure 34. Temperature (●) and gas utilisation (●) of the LCF biogas unit from Mar 2014 to Aug 2015.

Overlaying the gas use profile on the temperature graph shows a correlation between the amount of biogas produced by the unit and the temperature. Over the warmer summer months, the utilisation, and in this case, the production was up to twice as much as the winter months. There are two exceptions to this. The first exception is in October 2014, which, upon further inspection of the data corresponds to a small period of instability. The second outlier is at the end of December when it was revealed that the composting facility was closed for a week. As a result, the gas was not burned and thus, the gas use was reported as low. This week in December was the only week when the gas was not burned to completion daily and has been noted as an anomaly.

Exclusion of these two data points, the remaining data set was further analysed. It was postulated that the gas production would follow a linear relationship below 65 °C according to (Karangiannidis & Perkoulidis, 2009). Therefore, the normalised gas production was plotted against the temperature and shown in Figure 35.

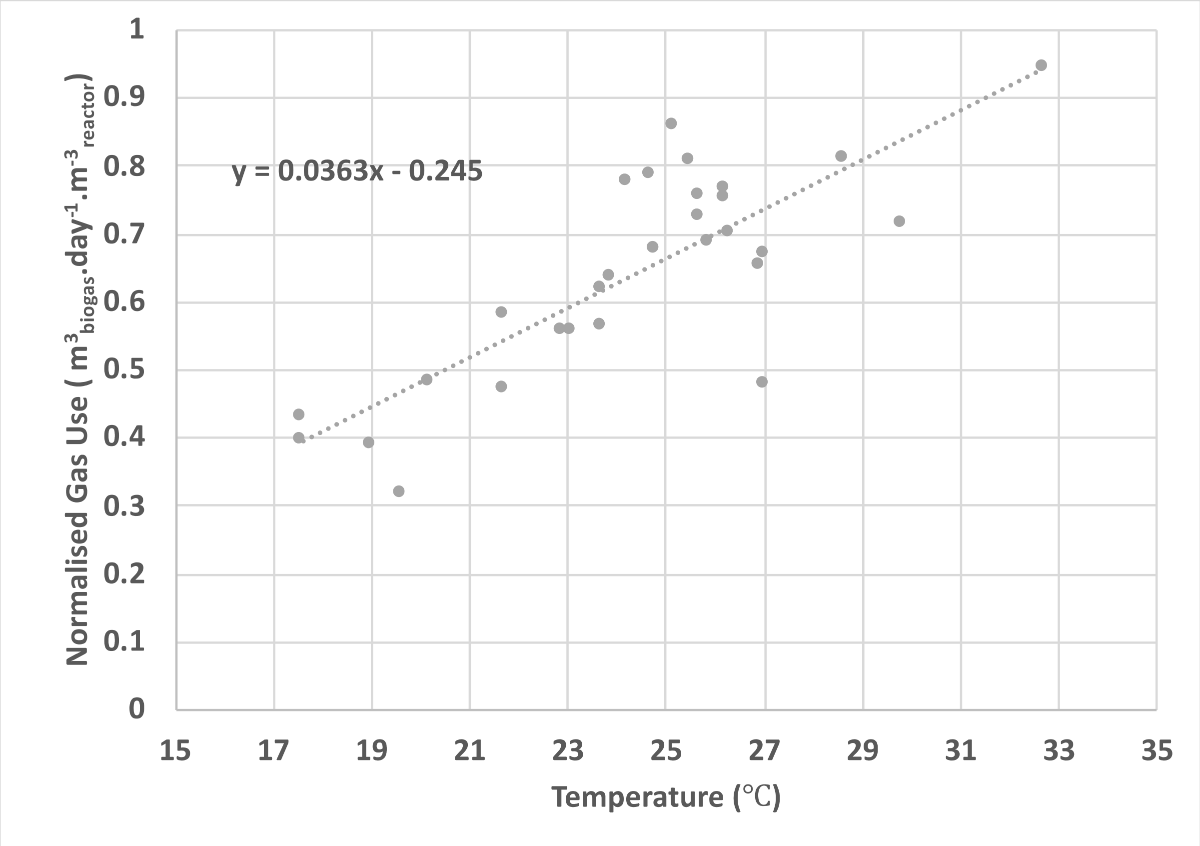

Figure 35. Normalised gas use vs temperature plot (●) with linear trendline (- -) for LCF biogas unit from Nov 2014 to Aug 2015

With the exclusion of the two exceptions, the gas use (in this case production) has a general linear relationship with temperature. The variances may be explained by inherent error in sampling methods for both temperature and gas production, as well as the variability in the feedstock. The same resultant plot would arise if the temperature was converted to Kelvin. Of note is the near doubling of gas production correlates with an increase in temperature of about 10 °C which is a heuristic in chemical reaction kinetics (Pauling, 1988).

6.2 Performance on Bokashi treated food waste

Four months (September 2015 up to and including December 2015) after the completion of the experiments described in Section 6.1, the biogas unit was fed with Bokashi treated waste instead of fresh food waste. During this period, there appeared to be no direct effect of the Bokashi on the gas production/utilisation, there was one notable observation and it was around instability. Referring back to Table 15, it was noted that there were seventeen instances of instability over the eighteen month period with a total of 43 kg of lime added for the purpose of rectifying instability. On average, that amounts to one episode of instability per month with just under 2.4 kg of lime added per month. Over the four months while the unit was fed with Bokashi treated organic waste, there was only one instance of instability, and the total amount of lime added to correct the acidity was 1.5 kg. Thus, it appears that Bokashi pre-treatment has a stabilising effect on the operation of the biogas unit, at least when using OFMSW as a feedstock food waste. The method of action of Bokashi is essentially a pre-fermentation and stabilisation of food waste for composting application.

According to Liu *et al.* (Liu *et al.*, 2006), two-stage anaerobic digestion allows for hydrolysis to occur at optimum conditions in the first stage, followed by methanogenesis at optimum conditions in the second stage, improving overall operational efficiency. It is postulated that the pre-treatment with Bokashi has essentially simulated a two-stage AD process, by which the hydrolysis occurs in its peak environment in the Bokashi bin, and the methanogenesis can occur at the methanogens peak condition in the biogas unit.

6.3 Experimentation with simple carbohydrates

From both Chapter 4 and 5, there was an indication that the feeding regime affected the stability of the biogas units. After the trial on Bokashi described in 6.2, there was then a further study to observe the effects of an increase in the amount of simple carbohydrates. Of the three types of feeding regime, namely simple carbohydrates, increases in household occupancy and changes in frequency/ratio, the first appeared as the simplest to mitigate for. While pre-treatment with Bokashi appeared to offer one solution, there remained a further theory to be tested. In Chapter 4, there was a long hiatus over the December vacation when the UCT biogas unit remained dormant, after which there appeared to be no issues of instability. Granted, the sampling method of measuring the pH changed as well, but the theory was that the microbes given the chance could adapt to a high carbohydrate feed, in the same way that they adapt to an OFMSW feed from cow manure. In order to investigate this further, there operational procedure described in Section 4.3.3.3 was undertaken. It involved a sharp spike in simple carbohydrate feedstocks, before and after a stepwise increase of the amount of simple carbohydrates. The total amounts of food waste, the specific amount of simple carbohydrates and the relative pH are shown in Figure 36.

Stage 1 was the initial shock treatment with 10 kg per day of simple carbohydrate OFSMW for five days. This caused the pH to drop irreversibly and the biogas unit was re-primed with cow manure and brought back to functional operation in Stage 2. From there, the biogas unit was reintroduced to OFMSW in the same way that is was migrated to OFMSW in Section 6.1.1. This time however, the portion of OFMSW which was simple carbohydrates was tracked and increased until the biogas unit was running completely on simple carbohydrates by the end of Stage 3. For two weeks after, the biogas unit fed varying amounts of mixed OFMSW – Stage 4. The shock of simple carbohydrates was then repeated in Stage 5 as it was done in Stage 1.

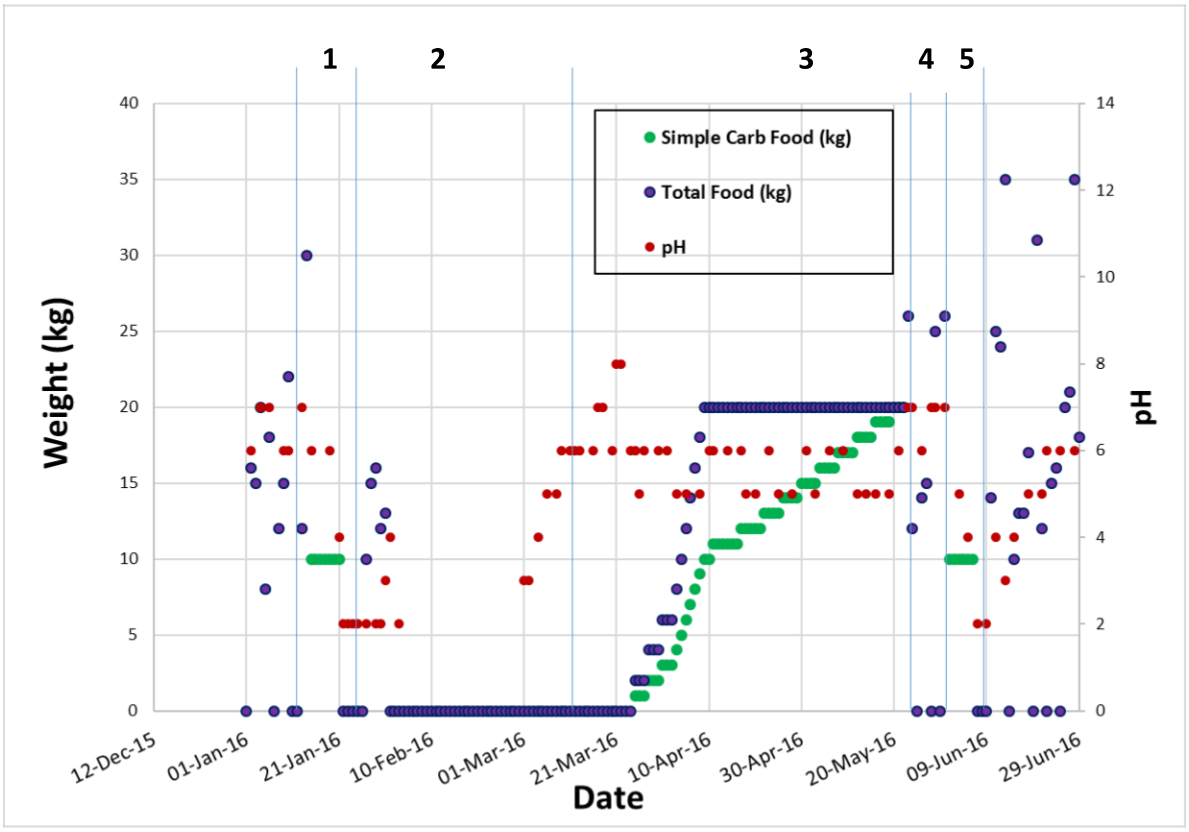

Figure 36. Time series profiles of total weight of OFMSW (●), weight of simple carbohydrate (●) on the primary axis, and pH (●) on the secondary axis for LCF biogas unit from January to July 2015

The process is discussed in more detail as follows. There was no recovery from the initial spike in mid-January. After a week of no feed and no sign of recovery of pH, some mixed organic waste was added but the biogas unit did not recover. Even after addition of lime, and then food waste, it appeared that the microbes were not resilient enough to recover performance. The unit was eventually re-inoculated with cow manure and the process took six weeks to return to operational functionality. This time, in the step-wise increasing feed of food waste, it was ensured that 50% of the mixed food waste was simple carbohydrates, until 20 kg was reached. At that point, the weight of food added was kept at 20 kg and the percentage of simple carbohydrates increased until it constituted 100% of the 20 kg was food waste. The biogas unit was then returned to the mixed organic waste for two weeks, before a spike of organic waste (10 kg per day over 5 days) the same as the spike in the first study was added. This time, even though the pH dropped, the unit was able to recover after a small waiting period and reintroduction of mixed food waste.

6.4 Summary and conclusions

Firstly, operational experience demonstrated that OFMSW can be the sole feedstock for an urban biogas system. Simple carbohydrates have been shown to cause the pH of the unit to drop and have an effect on the flame quality. If the load of simple carbohydrates is too high, it may permanently halt the production of biogas (i.e. the methanogenic population dies out). Mitigation for operational instability has been attempted in a few ways. Firstly, lime can be added to adjust the pH and has been proven to be successful even if it is the only method of correction for acidity. Secondly, pre-treatment of the OFMSW, simulating a two-stage reaction improves the operational stability. Lastly, it was investigated as to whether the microbes could adapt to the different feedstock by succession so that more resilient strains may be present to mitigate changes. This investigation had some success. Before the stepwise increase, the LCF biogas unit was unable to recover from a spike in simple carbohydrates. However, after an adaption phase it was able to recover after a similar spike in simple carbohydrates. Notably, there was a short hiatus needed for the recovery of the unit, which is another potential method to mitigate instability. Thus, the feeding regime has again been shown to influence the stability of small-scale biogas units in line with Hypothesis 2.

With regard to temperature, a correlation between temperature and productivity has finally been established. Since the gas used was the total gas produced, a direct correlation could be drawn between the increase in temperature and the increase in gas used/produced. Notably, the fluctuation of 10 °C was met with an almost doubling of biogas production, which is in line with the chemical reaction heuristic. Higher temperatures have allowed for higher use/production and in line with Hypothesis 2, temperature has been shown to have an effect on the productivity of small-scale biogas units

Lastly, reflecting on Hypothesis 3, the LCF unit, even though it used the same application, had active management and an operator on site who used the application daily and was contacted daily on the mobile device. Expanding on this, it may be safe to say that the tool was better and more frequently utilised because the with more active management via the application.

Chapter 7: Conclusions

This thesis set out to investigate a particular version of biogas technology, viz. small decentralised installations, as a contributor to achieving sustainable urban development in Africa's cities, through investigations into the potential and limitations of the technology in various situations. The investigation was structured into three parts, covered in Chapters 4, 5 and 6. This final chapter of the thesis first synthesises the findings from the three results chapters, then proceeds to draw conclusions by revisiting the hypotheses posed in Chapter 3, and finally presents recommendations, both for further research and for practise.

7.1 Synthesis of findings

In this section, the findings of the various chapters are synthesised. The first objective of this thesis addressed through all the results chapters, was to understand how stable small-scale urban biogas units can be operated. This was largely inferred from changes in pH and flame quality, supported by analyses of gas burn times. In the first study with the UCT biogas unit, it was shown that the instability, as reflected by a decrease in pH occurred after a large amount of simple carbohydrates had previously been fed to the biogas unit. In the second study, it was shown that all small-scale units were prone to episodes of instability. These instances were often investigated through a monitoring system to determine a cause, which were typically linked to the feeding regime, specifically the amount of simple carbohydrates fed to the unit, the organic loading rate or simply a change in the ratio/frequency of the feed. Learnings from these two chapters led to the formulation of an investigation of a final biogas unit at a local composting facility. This unit was slowly migrated onto OFMSW initially by stepwise increase and the feeding regime was manipulated. Furthermore, after an initial shock of simple carbohydrates caused permanent souring, resilience was shown to improve after the same shock was conducted, but after a slow stepwise adaption to simple carbohydrate over 3 months. Mitigation techniques in the first study included addition of lime, while a long hiatus was also shown to contribute to a more stable biogas unit in later periods. In the second study, a small break in feeding was recommended to the biogas operators and it showed some success. In the final study, lime was used very actively with noted success, but more notably, the unit demonstrated improved stability after the feedstock of OFMSW was pre-treated with Bokashi, needing a lime buffer only once over the four months of operation on Bokashi treated waste (c.f. approximately one a month in normal operation on untreated OFMSW).

The second objective was to advance the understandings of operational productivity of small-scale biogas units. Normalised gas use, and gas utilisations were used as indications of productivity in the first two studies, in which regard, the learnings were limited, as those calculated variables are a function of the gas used, rather than the gas produced. The maximum theoretical biogas would be a function of the hydraulic residence time, which was not measured, as it was assumed that all the volatile solids in the substrate were converted to biogas, which may have not been the case. Secondly, gas utilisation is a measure of gas used, not necessarily gas produced. Even in the cases with the highest gas utilisation, there was never an instance when the gas supply was completely exhausted, indicating that the users used what only what they needed, and not what they produced. The latter is, however, an indication that many installations were under-utilised.

That being noted, the first study showed an improved gas utilisation over ten weeks in the summer months compared to five weeks in the winter months. In the second study, five of the six digesters which were operational over the winter months showed a lower gas utilisation in those months. In the final study, gas was burned until it was completely finished, meaning that the gas used was the actual gas produced. In this study, the gas utilisation tracked the temperature profile, showing almost a doubling in normalised gas utilisation in summer months, which had an average daytime temperature which was 10 °C higher than winter months. Furthermore, it is noted that productivity is linked to stability. From the second study, it is noted that the unit in the Eastern Cape which was plagued by instability was the least productive and suffered from poor gas quality. In five of the units in the remote monitoring study there was no noted decline in gas utilisation, but in the other five, where a decline in utilisation was observed, the majority of incidences also reported a decline in gas quality in the episode of instability.

Lastly, with regard to the final objective, the remote monitoring work was an attempt to monitor and then build an early detection system as part of operational knowledge support. The results from the second and third study showed that this was successful to a degree. In the second study, the monitoring system was successful at detecting incidences of instability and the recorded data, coupled with contact with the user was able to determine the cause of such. In the third study, with more active management and use of the system, instances of instability were mitigated quickly and the digester itself was operated within a set of guidelines. This shows that the system would be most significant with engaged users.

7.2 Conclusions

The first major conclusion is around the stability of the biogas units. It was hypothesised that feedstock variability would be the key factor affecting the stability of such small-scale systems. As per the synthesis above, an increase in the simple carbohydrates in the feeding regime (most often observed when the feedstock was OFMSW) was responsible for a decline in the pH in three of the biogas units over eight different periods. In the LCF unit, a large amount of simple carbohydrate caused permanent souring of the unit. In two units, where the digesters were connected to the sewage outlet, it was an increase in the organic loading rate, via an increase in household occupancy. For the two units fed with agricultural waste it was a change in the feeding ratios/intervals which were attributed as the cause of instability. These can be explained as follows. Firstly, anaerobic digestion is a staged process, the first of which is a hydrolysis phase which can occur very quickly with simple carbohydrates, possibly lowering the pH of the system, adversely affecting the balance of biological agents. Increase in household occupancy (i.e. an increase in volume) and changes in the feeding regime also caused instability. The various mitigation techniques, namely; addition of lime; interaction with users; pre-treatment with Bokashi; cessation of feed and an adaption for resilience, were shown to be effective in varying degrees at combatting instability. Therefore, the hypothesis that the feeding regime would affect stability was proved to be true, that feedstock variability, not just in terms of composition, but also in terms of volume is the key factor affecting stability.

The second part of the investigation focused on productivity of small-scale biogas and the effect that climate (thereby ambient temperature) would have on the gas production. The method of quantification proved limited in the first two studies, but a small tweak in the active management of the last unit allowed the same measurements to infer gas produced, rather than just the gas utilised. In the second study, it was shown that the units at institutions were showed better utilisation than the units at domestic households, thus the efficiency of use is more a factor of the demand for the gas. Despite the limitations the gas utilisation of individual units do appear to follow a seasonal profile, noting that the actual percentages are a function of hydraulic residence and therefore, while the trend is observed, the actual numbers may not be accurate. The second study, despite providing some insight, remained inconclusive. The final study did show a clear link between temperature and productivity. The second hypothesis can therefore only partially be proven true. Under controlled conditions, yes, the productivity is linked to the temperature. However, under uncontrolled conditions, based on evidence here, when gas utilisation is not always at maximum the temperature profile seems to be less important than the type biogas installation and the demand for gas.

Lastly, it was postulated that smart monitoring of key parameters would improve the stability and productivity of small-scale biogas units. Firstly, two parameters which would typically need laboratory equipment to measure, could be approximated by more crude measuring techniques. Also, flame quality was a useful simple measurement of gas quality. The monitoring of key parameters, even with crude techniques and limited information was able to inform the stability and also productivity of small-scale units. Moreover, the system allowed for some level of interaction and knowledge sharing to mitigate for instability. Thus, speaking towards Hypothesis 3, not only was the monitoring of key parameters useful to improve the stability and productivity of small-scale biogas units, but when strongly championed, it could be used to gain insights into the factors which affect the stability and productivity of the system, as well as further investigate mitigation techniques for instability.

In summary, tying this back into the productivity and stability investigations in the context of the actual deployment and operation of the technology, the parameters which most greatly influence the stability and productivity of biogas units have been identified as feeding regime, and then the installation type and the climate respectively. The monitoring of these parameters can be done relatively easily with low tech innovations to provide meaningful and useful data with which to inform a monitoring infrastructure, which is itself able to pre-empt perturbations and 'rescue' a unit which is about to lose productivity or stability. This knowledge support system mentioned above, needs a technician who understands the process of anaerobic digestion on the other end of the smartphone to give feedback to the champion. Thus, the third hypothesis, stating that remote monitoring would be useful to safeguard investment, was proven true.

Overall, when considering small-scale biogas as a renewable energy option for urban Africa, there are incidences of instability which arise frequently in all installations. These incidences will impact on the productivity of the biogas unit. This work shows that it is possible even with limited information and instrumentation to pick up these incidences, and moreover, to mitigate for these, either through monitoring, or pre-treatment of heterogenous feedstocks. The technology does, however, come with its own unique set of challenges. Its application and reach are limited by feedstock and would still need to be part of a group of technologies to meet all the energy demands (noting the capacity of 5% of energy using waste-based feedstock only). Having stated that, the additional advantages of waste management and sanitation need to be re-iterated. Thus, through the lenses of productivity and stability, small-scale biogas may be an important technology, but comes with limitations and operational challenges, the latter which can be mitigated by knowledge support, possibly through smart monitoring.

7.3 Recommendations

7.3.1 Recommendations for further research

One of the more interesting outcomes of this work is the synergistic effect of Bokashi pre-treatment on the stability of a biogas unit run on heterogeneous food waste. In effect, pre-treatment with Bokashi has simulated a two-stage digestion process, with the feed to the second stage (the actual biogas plant) having been conditioned and stabilised. The function of Bokashi is to stabilise organic waste, so it is not unexpected to have this outcome. Since this part of the investigation was limited to one experiment under field conditions, it would be useful to have laboratory scale and then pilot scale tests to confirm and quantify these observations, inter alia to determine the exact quantities needed, and the necessary fermentation times with different feedstocks. Pre-treatment was also only one of the proposed mitigation techniques. Others included a hiatus (with a noted consequence of not having a waste treatment option for some time) and direct pH adjustment with lime. The relative effectiveness of these techniques along with an economic analysis, could be quantified in a completely separate research study.

For the productivity investigation, it would be useful to glean further insights into the real gas utilisation at institutional levels versus domestic ones, as it currently appears that domestic (probably more affluent) users have lower gas utilisations than institutions which would value the energy more. This would involve the refinement in the method of quantification of productivity possibly with the involvement of the measurement of hydraulic residence time to better inform the maximum theoretical biogas calculated. This could be achieved through another monitoring study or a direct investigation.

Lastly, it is interesting to note that the entry point for biogas was from energy provision, but the final investigations were carried out from a waste management angle. The obvious link is waste-to-energy practices. It may be useful to assess this technology from a waste treatment angle first with the added benefit of energy provision.

7.3.2 Recommendations for practice

This research has initiated the case for the actual deployment of small-scale biogas to be in urban Africa. A region with the correct climate, and a situation in which the proactive/incentivised champions, armed with some knowledge, a smartphone and access to technical support can be allocated to individual units, for a number of units to be deployed in an urban setting. The context would also ideally utilise the digestate to make a stronger economic case for the programme. Also, the current system had the technician logging in to check each unit and go through data, while the overall system required, would need to be more complex, at least on the side of the technician, who would need automatic alerts and reports to be sent to them if there were potential issues on the horizon. What this means for decentralised installations in Africa is as follows.

The mobile application for this work was built in JAVA to run on basic Nokia Smartphones in 2011. Since then, iOS and Android have become the global standards. If this work were to be continued, then a compatible application should be developed. Advances in technology could allow the mobile application to have more functionality. One consideration during this study was to include a camera function to read the colour of the pH test strip as an additional feature to aid those suffering from red/green colour-blindness and/or to reduce human error. Another option could be to more accurately understand the feedstock with a photo. Also, the application was loaded onto a separate phone, and it is likely that if it were installed on a personal device, it is much more likely that it will be used daily.

Finally, with reference to sustainable development goal around cities and communities, I believe that given the right conditions, biogas can be an important supplementary technology, and should be considered (in conjunction with other technologies) when planning smarter, sustainable communities.

7.4 Outlook

Over the time of this investigation, the first large-scale commercial waste-based biogas plant in South Africa was commissioned in Bronkhorstspruit. At the time of the initial submission, in 2017, the commissioning of the first biogas plant which will receive municipal solid waste was underway. This project could however not be successfully commissioned as it ran out of operating capital before all its components could be demonstrated to be working; several were novel and never built at this scale before. Energetically, it is always more efficient to have decentralised operations, but this research has also shown that small-scale installations have very low overall efficiencies and are prone to instabilities. However, a new biogas unit was commissioned in late 2018 at a shopping centre in Cape Town and incorporated elements of remote monitoring. This deployment of many such medium-scale units may be what is needed to address energy challenges of developing cities. In Africa, therefore, decentralised may mean medium scale units at shopping centres, which could justify investments and ensure operational success. Of note is that the source separated organic waste for the LCF unit was sourced from a nearby shopping mall. Thus, as landfill prices rise, there will be a need for waste management alternative (not just energy alternative) and formerly costly alternatives become feasible. In that regard, biogas should therefore not be too far in the future, at least at the optimal institutional level.

There has been some debate about whether we are in a new industrial revolution, or whether we are just in a second phase of the previous, third industrial revolution. Either way, the advent of the Internet of Things, means that there are now platforms and systems which rely on trackers, sensors and devices, all online and working together. There is definitely an opportunity for application for IoT in the rollout of small-scale biogas. Real-time data and machine-to-machine communication would allow data to be pushed to alert the technician. There are naturally concerns about job replacement, but if this were to be used on the right scale, there would be enough employment created from the deployment of the technology that monitoring could be left to smart sensors and the overall costs of knowledge support would be cheaper, making small-scale biogas more feasible.

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Appendices

Appendix A: The sustainable development goals (UN, 2016)

- Goal 1. End poverty in all its forms everywhere
- Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
- Goal 3. Ensure healthy lives and promote well-being for all at all ages
- Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
- Goal 5. Achieve gender equality and empower all women and girls
- Goal 6. Ensure availability and sustainable management of water and sanitation for all
- Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all
- Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- Goal 10. Reduce inequality within and among countries
- Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 12. Ensure sustainable consumption and production patterns
- Goal 13. Take urgent action to combat climate change and its impacts
- Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
- Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
- Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
- Goal 17. Strengthen the means of implementation and re-vitalize the Global Partnership for Sustainable Development

Appendix B: Glossary of terms

Green energy (Johanssen, et al., 1993)

- Energy sources which are known to be non-polluting and that are fundamentally environmentally friendly

Rebound effect (Berkhout, et al., 2000)

- Technological progress makes equipment more efficient and the positive effects of green goods and services could be cancelled out by increases in production and consumption, as revenues from more eco-efficient technologies are used to consume more elsewhere in growing economies

Sustainable development (Goodland & Daly, 1996)

- Development without growth in throughput of matter and energy beyond regenerative and absorptive capacities

Sustainable degrowth (Schneider, et al., 2010)

- Equitable downscaling of production and consumption that increases human well-being and enhances ecological conditions at the local and global level, in the short and long term as compared to unplanned degrowth which equates to economic depression.

Sustainable energisation (Nissing & von Blottnitz, 2010a)

- The transitional process of progressively meeting primary and early secondary energy service needs of a poor economic subgroup (second economy) through the delivery of an enhanced quantity, quality and/or variety of accessible and affordable energy services, enabling the sustainable development of the considered subgroup based on poverty alleviation and economic development, as well as the optimisation of the energy service supply network from a lifecycle perspective.

Appendix C: The IPAT equation illustrated

The IPAT equation (Ehrlich & Holdren, 1971) is used to highlight the importance of technology in the role of reducing impacts.

Equation: $$Impact = Population \times Affluence \times Technology$$

Using carbon emissions: $$kg_{CO_{2_{equivalent}}} = capita \times \frac{GDP}{capita} \times \left[\frac{kWh}{GDP} \times \frac{kg_{CO_{2_{equivalent}}}}{kWh}\right]$$

Using waste production: $$kg_{waste} = capita \times \frac{GDP}{capita} \times \left[\frac{kg_{consumed}}{GDP} \times \frac{kg_{waste}}{kg_{consumed}}\right]$$

If the population and the population and the affluence of a country keep increasing, then the efficiency of technologies need to increase significantly to counteract the impacts. In the first example, the carbon emissions per kWh produced is the space where green technology features.

However, (Alcott, 2010) shows with his contribution, policies to control population or consumption are likely to backfire through rebound effects (see definition in Appendix B), i.e. declining resource prices as demand for their use falls, triggering increased use elsewhere later. With reference to the equation, a right-sided strategy allows any of the other two to rise if one is reduced while rationing, imposing caps or Pigouvian taxation of resources or pollution necessarily lower the impacts. This is proposed to be simpler compared to multiple sectoral consumption, population and technology policies.

Appendix D: The potential impact for biogas in the City of Cape Town

The following is a 'back-of-the-envelope' calculation for the purpose of giving an estimate of the potential of biogas from MSW in the City of Cape Town. Assumptions are all stated clearly.

- The waste generation to landfill in the CoCT peaked at 2.8 million tpa 2007/8, and has declined to some 1.8 million tpa in 2008/9 (CoCT, 2010), thus an average of 2 million t/annum is used.

- The current OFMSW is 50%

$$Mass_{OFMSW} = 50\% \ \times 2\ 000\ 000\ tpa = 1\ 000\ 000\ tpa$$

- OFMSW may have a high moisture content (40-80%) (Munganga, et al., 2010), thus use an average of 60%

$$DryMass_{OFMSW} = 40\% \ \times 1\ 000\ 000\ tpa = 400\ 000\ tpa$$

- 30% of OFMSW is volatile solids, based on (Munganga, et al., 2010)

$$VS_{OFMSW} = 30\% \ \times 400\ 000\ tpa = 120\ 000\ tpa$$

- BMP is on average 200 ml/g VS for waste streams, based on (Munganga, et al., 2010)

$$Biogas\ Produced = 120000tpa \ \times \frac{1\ 000\ 000\ g}{1\ t} \times \frac{200ml}{g} \times \frac{l}{1000ml} \times \frac{m^3}{1000l}$$
$$= 24\ 000\ 000\ m^3pa$$

- The heating value of biogas (at 60% methane) is 578 btu/ft^3 = 21.6 MJ/m^3

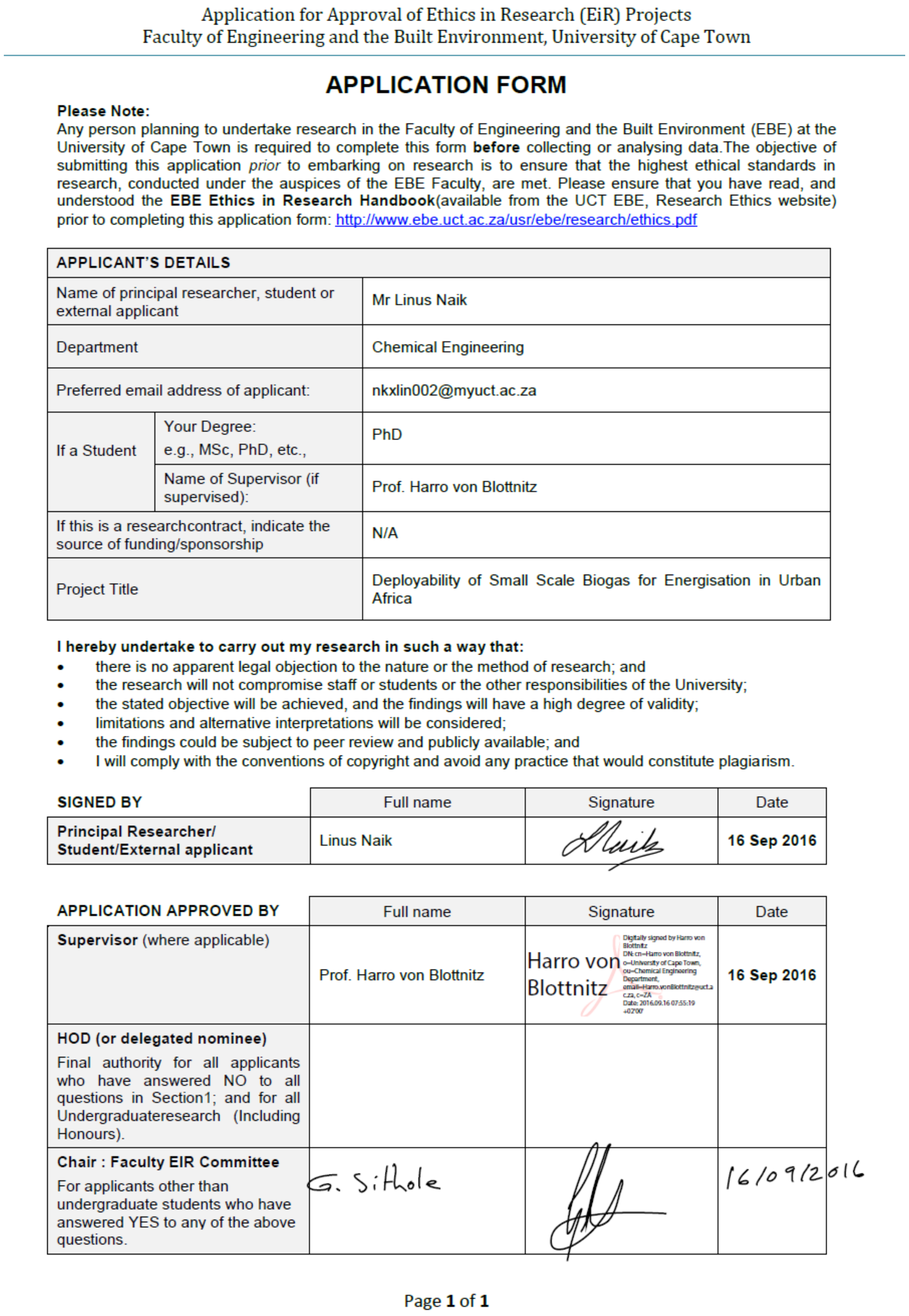
$$Energy\ produced = 24\ 000\ 000\ m^3pa \ \times \frac{21.6\ MJ}{m^3} \times \frac{PJ}{1\ 000\ 000\ 000MJ} = 5.18\ PJ$$

- Given that the total energy demand of the CoCT is 130 PJ (SEA, 2010). Over 50% of this comes from the transport sector (and biogas can be used as vehicle fuel). Thus, the potential provision of energy from municipal solid waste via biogas in the City of Cape Town is:

$$\frac{5.18PJ}{130PJ} = 4.3\%$$

If a thermal efficiency of 35% (Eskom, 2011) assumed, i.e. biogas is used for electricity generation, then the energy demand met drops to 1.5% that required by the city.

Appendix E: Ethics Clearance



Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data.The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook**(available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Mr Linus Naik
Department		Chemical Engineering
Preferred email address of applicant:		nkxlin002@myuct.ac.za
If a Student	Your Degree: e.g., MSc, PhD, etc.,	PhD
	Name of Supervisor (if supervised):	Prof. Harro von Blottnitz
If this is a researchcontract, indicate the source of funding/sponsorship		N/A
Project Title		Deployability of Small Scale Biogas for Energisation in Urban Africa

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Linus Naik		**16 Sep 2016**

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Prof. Harro von Blottnitz	Harro von Blottnitz Digitally signed by Harro von Blottnitz DN: cn=Harro von Blottnitz, o=University of Cape Town, ou=Chemical Engineering Department, email=Harro.vonBlottnitz@uct.ac.za, c=ZA Date: 2016.09.16 07:55:19 +02'00'	**16 Sep 2016**
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).			
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	G. Sithole		16/09/2016

Page **1** of **1**

Appendix F: Associated projects

F1: The UCT residence biogas project brief

Objectives and approaches

This project aims to demonstrate that it is technically feasible to produce methane gas from source-separated wet waste on campus, and to use this gas for cooking purposes. Beyond the potential wider application of this technology at UCT, it is important for several current research projects to demonstrate that decentralised biogas technology can be deployed in an urban setting; it is so far regarded to have mainly rural applications.

This project foresees bringing onto campus a 6 m^3 pre-fabricated biogas unit, the BiogasPro (Agama, 2010) if the residence kitchens where waste is already sorted into recyclables and wet waste. The unit would take between 20 kg and 40 kg of organic waste from the kitchen per day. The unit can be installed above-ground although a below-ground installation is usually preferred. Treated effluent should go to sewer, and sludge will have to be recovered and disposed of (or utilised for composting) from time to time.

Status of the project

Relevant stake-holders were consulted with regards to installing a biogas unit at one of the university's residences. Two of the university departments, Properties and Services (P&S) and Student Housing and Residence Life, were identified as important stakeholders to engage for a successful implementation of the project. After a general engagement of stakeholders that was meant to introduce the idea to them, discussions on identifying a suitable catering residence where the biogas unit would be installed were held between the task team and stake-holder representatives. Leo Marquard Hall catering residence was selected as a pilot site. Once the pilot site had been identified, a decision was taken to carry out a formal monitoring and quantifying of food waste generated per meal. The monitoring was done over five weeks, as much as 38 kg of food waste was generated per meal which is sufficient waste for the pre-fabricated unit to be used.

During the initial stakeholder engagements, several concerns were raised; these included odours problems and probability of perpetuation of existing flies' problem. A consensus was reached for relevant stake-holder representatives to thus pay a site visit where one of the biogas units installed by technology supplier is in operation. The chosen site was Goedgedacht Trust farm in Riebeek Kasteel where both a pre-fabricated and concrete-constructed unit are installed. The visit addressed the issues raised in the previous meeting of odours, flies, maintenance and gas quality.

Implementation plan:

Consent from the Property and Services department to go ahead with the proposed plan has already been granted. The technology providers (AGAMA Energy) are busy with the detailed design phase after survey of the site. Detailed engineering design tailor-made for Marquard Hall is to be approved either internally by P&S. Installation is estimated to happen within the next six weeks.

Once installed, the unit would be operated on monitored diets for a period of 12 months, and its performance regularly evaluated by the E&PSE research assistants, with an option of being shadowed by the kitchen staff to take over at a time that will be discussed at a later stage. However, our team will continue to monitor the performance of the unit from a research perspective However, after these 12 months there will be a better understanding of the ongoing maintenance routing and cost, and this will be negotiated with the relevant UCT departments.

F2: The Abalimi biogas project brief

Objectives and approaches

This project aims to provide biogas as an energy source in a community garden. Abalimi Bezekhaya is a community garden located in Philippi in Cape Town. The site doubles as a community kitchen and a crafts workshop. The land is owned by the municipality and residents around the area are allowed to grow crops for subsistence and sale. An inflatable bag biogas unit was donated by Silverlight energy and installed at the community garden to provide energy for cooking. Technical support is provided by EwB who consulted E&PSE for assistance. Construction was done by Silverlight in conjunction with EwB.

Status of the project

The unit was installed in October 2013. The gas produced is used in the kitchen to prepare meals, and the digestate was used as an additive to composting.

F3: Aquatest: Remote Water Quality Monitoring (UCTCivEng, 2011)

Objectives and approaches

The Aquatest Research Programme is an international, multi-disciplinary consortium led by the University of Bristol. The aim is to deliver a water test that can be used widely in developing countries, with a sustainable basis for manufacturing, distributing and marketing the Aquatest device. Close collaboration with researchers and potential users in South Africa and India will help to develop a device that meets users' needs.

The Global Development Program of the Bill & Melinda Gates Foundation has provided support to the this second phase of the Aquatest programme with a grant of US $13 million. The award has been made to the University of Bristol who will lead and coordinate the consortium of participants. Other consortium members include the World Health Organisation, University of California – Berkeley, University of Southampton, University of Cape Town, PATH, Aquaya Institute, and the UK Health Protection Agency.

Objectives relevant to South African field studies

- Develop a low-cost water test device that is highly portable, simple to operate and gives a clear indication of water quality. The device will be designed for general use in the field and will be developed to ensure reliable use in low resource settings (University of Bristol)
- Design and development of a smartphone application that allows transfer of the water quality results and observed aspects (risk assessment, sanitary inspection forms) into a centralised database (University of Cape Town)
- Integration of water quality results into existing information systems (University of Cape Town)
- Design and development of a feedback loop between communities and supporting authorities, e.g. information regarding status of water quality, routine water quality information, targeted requests (University of Cape Town)
- Assess the impact of water quality information flow over one to two years(University of Cape Town, University of California - Berkeley, University of Bristol, WHO)
- Test the information flow system in India (Indian partner organisation)
- Develop an understanding of barriers to implement the water quality test kit and the information management system (WHO)
- Develop techniques for combining routinely collected water quality data with other spatial data sets to improve monitoring and targeting in the water sector (University of Southampton)

These are the major objectives that will apply to South Africa. Since the AQUATEST water quality test design is only expected to be finalised next year, the information system backbone will be developed and tested using existing water quality test kits, such as H2S test.

For this study we will be targeting professional and semi-professional users working in rural environments. This includes municipal officials as well as community water committees, supply caretakers or dedicated community resource persons. The focus will be at community management level and the information transfer of water quality status to supporting/local authorities.

The study and the study area will be selected to be representative of a cross-section of developing countries, not only of South Africa.

Appendix G: Abstracts from relevant conference papers

G1. WasteCon 2012 (Naik, et al., 2012)

Onsite anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) has the potential to address a waste management problem while at the same time providing energy. To show that this can be done in urban settings, a household scale anaerobic digester was installed at the Leo Marquard Hall residence of the University of Cape Town in early 2011. Fed on kitchen and canteen wastes, the produced gas is used in the kitchen to supplement cooking energy requirements.

This paper presents operating experiences for the first 13 months, focusing on the productivity and stability of the 6m^3 pre-fabricated digester. Among the parameters monitored were pH, temperature, pressure, burning-time and the type of food fed to the unit. Daily burning times of up to an hour on a 4.5 kW biogas stove have been achievable at times. The type of food waste and its quantity were the primary factors which affected the pH of the unit. High amounts of simple carbohydrate in the feed caused a drop in pH and at times, lime was added to buffer the reactor back into operating range. The energetic efficiency of the digester as operated was estimated as the ratio of energy in gas burnt to energy content of the food input and found to have increased from 41% during a five-week winter period fairly early on in the project to 51% during a ten week summer period later on.

The study has shown that small scale biogas production from the organic fraction of municipal solid waste is feasible in an urban setting, as long as strategies are in place to control the feed rate and for quick detection and action to ensure continued productivity after process upsets

G2. WasteCon 2016 (Naik, 2016)

Organic waste typically comprises the largest fraction of non-recycled general waste in South Africa. Anaerobic digestion, Bokashi treatment and composting are alternative treatments for organic waste, which harness its energy and/or nutrient value.

This paper presents operational experiences at a composting facility, which has a $6m^3$ pre-fabricated anaerobic digester on site. A portion of the pre-sorted organic waste from a mall was fed to the anaerobic digester to produce biogas (used on site) and digestate (added to compost). Another portion was treated at the mall with Bokashi bran and transported to the composter to be added to other compost heaps.

Anaerobic Digestion with use of the biogas on site as well as the composting of the digestate had a normalised profit of R 0.67 per kg of organic waste processed compared to R 0.28 for Bokashi treatment with composting. However, anaerobic digestion required technical expertise, had a high capital cost and was subject to efficiency fluctuations with temperature

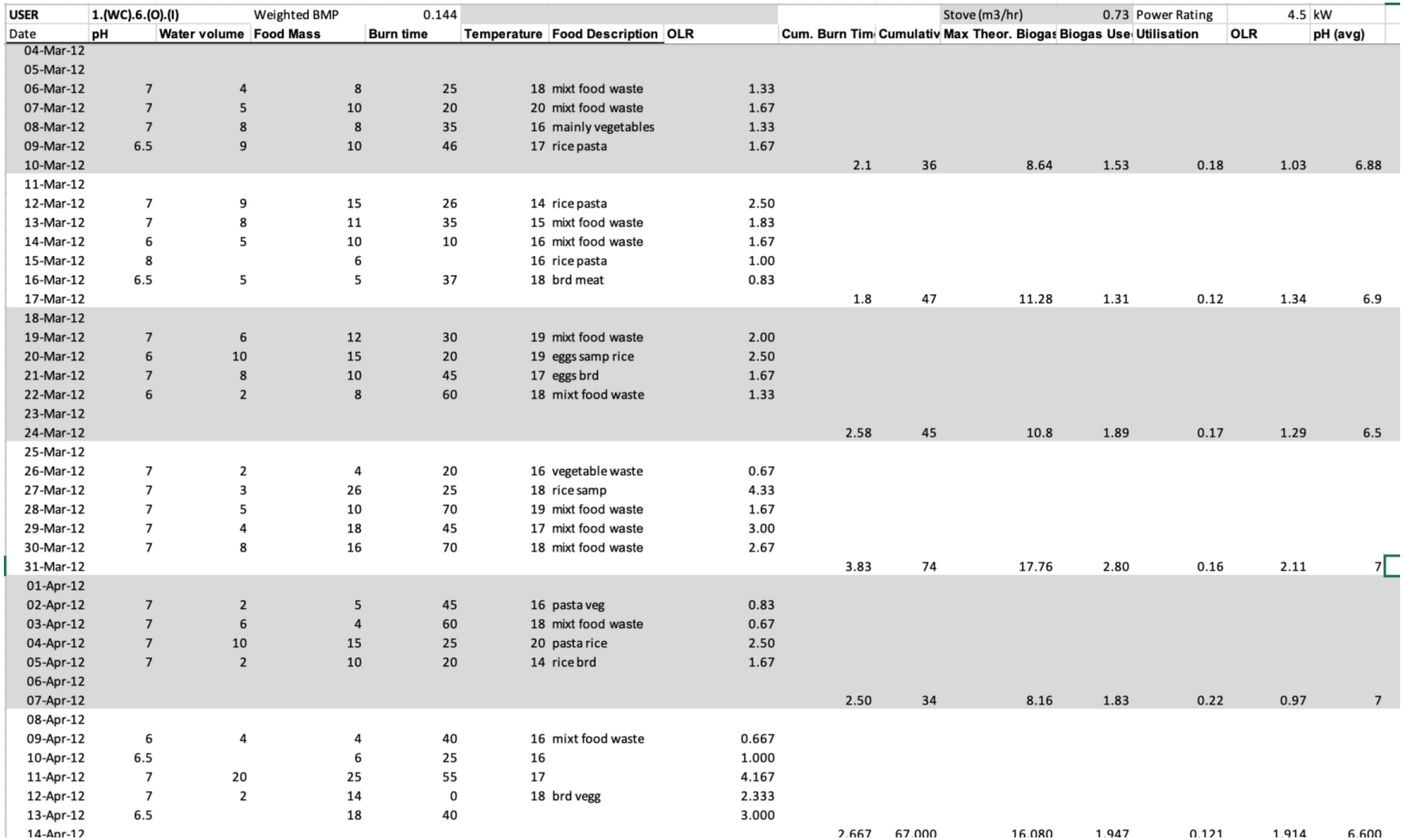
Appendix H: Sample Data

A large amount of raw data was generated. Displaying all the data here would take up 200+ pages. Therefore, typical sample data is given and the full data set can be made available on request.

H1. Raw data sample from UCT biogas unit for Phase 1

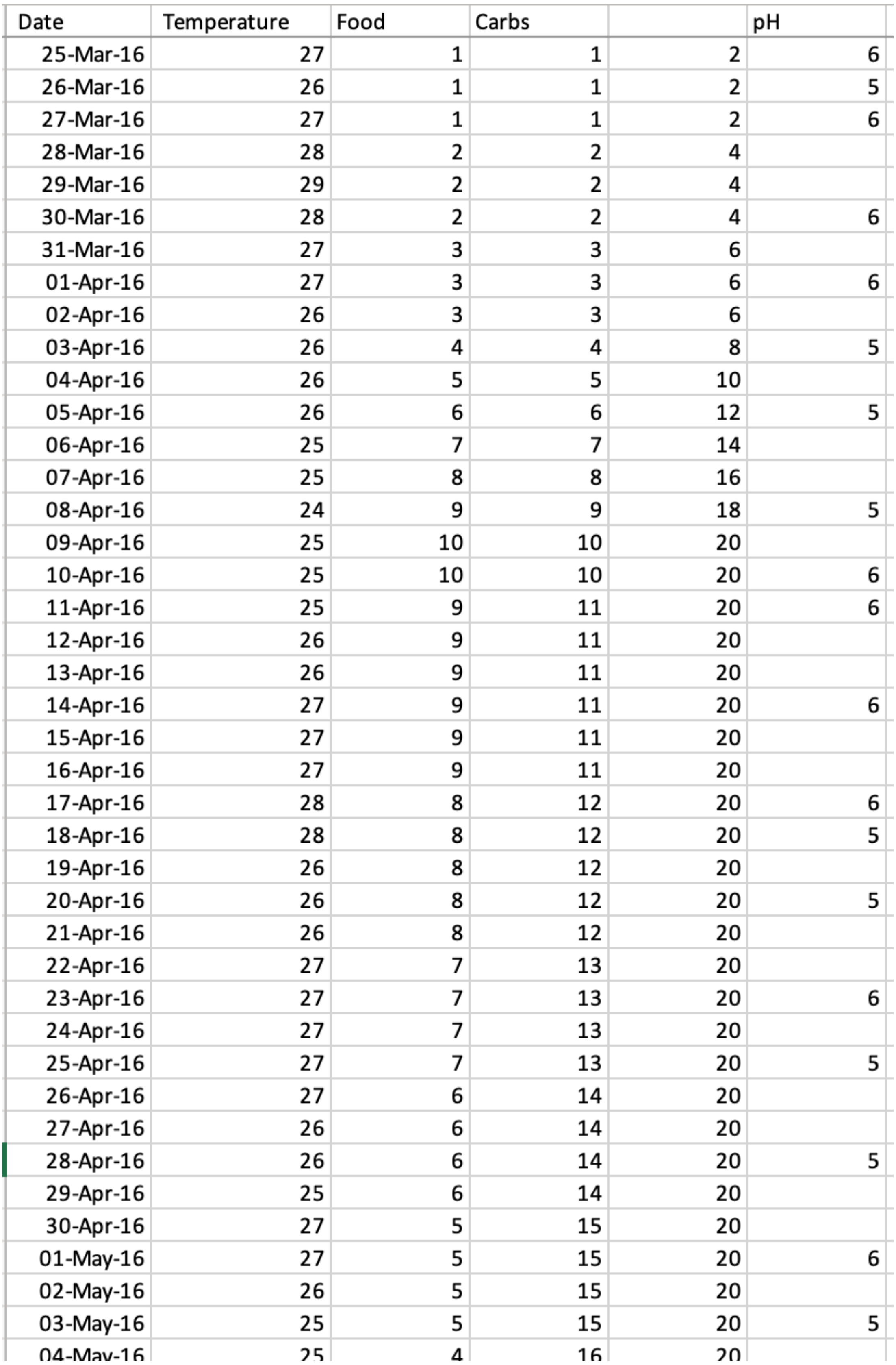
	Date Taken	pH	Water volume	Food Mass	Gas Pressure	Temperature	Food Description
	28-3-2011	6					
	29-3-2011	6.5					
	30-3-2011		2	1	4		a
	6-4-2011	9.2			0.8		
	7-4-2011	9.2	10	7	0.8		rice,stew,pasta,chicken,potatoes
	8-4-2011	9.1	10		1		
	9-4-2011	9.3			1		
	10-4-2011	9.21	14	7	1.2		70 per cent rice, 20 chicken ,rest veggies
	11-4-2011	9.34	10	5	1.2		rice,chicken,mutton stew, lasagne
	12-4-2011	10.39	10	5	1.4		breakfast waste. Pancakes, beans, bread, cereal
	12-4-2011	10.39	10	5	1.4		pancakes,beans,bread,cereal
	13-4-2011	9	10	5	1.2		mostly rice amd meat
	15-4-2011	9.25	16	8	1.2		chicken,rice,fruits,lattice,carrots and tomatoes
	19-4-2011	7.02	14	7			chicken rice.pies, few vegetables
	22-4-2011	6.45					rice,stew,little bit of chicken And mixture of veg
	24-4-2011	5.92	20	7			stew,pie,rice,lapagse,few vegies
	27-4-2011	6.71	20	8			rice,chicken,mince meat and vegetables
	28-4-2011	6.89	20	7.5			rice,chicken,soup,mince and few vegetables
	29-4-2011	7	20	7			rice, chicken, mince,vegetables…..
	30-4-2011	7.02	20	7	2.2		vetkoek,mince,pap,stew and vegetables
	1-5-2011	7.02	20	7	3.2		chicken,rice,stew and various vegetables
	2-5-2011	6.89	20		1.6		rice,mince,spaghetti,chicken and variety of vegies
	3-5-2011	6.77	20		3.2		rice, chicken,fish and vegies-mainly potatoes
	4-5-2011	6.67	20	10	3.2		pizza,rice,chicken and a variety of vegies
	5-5-2011	6.65	20	10	2.8		rice, chicken pasta salad
	6-5-2011	6.7	20	10	2.8		fries, fish, veggies
	7-5-2011	6.69	20	10	3.1		pasta, pie
	9-5-2011	6.6	25	12.5	3.4		potatoe,mayo, chicken,egg
	10-5-2011	6.54	25	12.5	2.4		rice,mince,chicken and vegies
	11-5-2011	6.6	25	12.5	2.8		beef,rice,chicken,salads and spaghetti
	12-5-2011	6.43	25	12.5	2.8		chicken,pap,beef,fruit salads
	14-5-2011	6.31	25	12.5	2.8		spaghetti,mince,rice,chicken
	15-5-2011	6.2	25	12.5	3.3		lamb stew,rice,vegies,chicken
	16-5-2011	6.2	25	12.5	3.3		fat kok,mince,rice,fruit salad and vegies
	17-5-2011	6	25	12.5	2.9		chickem rice and vegies
	18-5-2011	6.22	25	12.5	4		spaggheti,rice ,beef,mince
	18-5-2011	6.49	30	12.5	2.2		rice,chicken mince,spaggheti and vegies
	19-5-2011	6.52	30	12.5	2		pap,beef,vegies,rice,chicken
	20-5-2011	6.63	30	12.5	3		rice,chick,stew,vegies
	21-5-2011	6.63	30	12.5	2.5		rice,chicke, potato salad and a variety of vegies
	22-5-2011	6.59	30	12.5	3.3		chicken, lamb,rice and pap
	23-5-2011	6.61	30	12.5	3.3		chicken,rice,vegies,fish and pies
	24-5-2011	6.58	30	12.5	3.1		chicken,mince,fat koek and rice
	25-5-2011	6.43	30	12.5	2.8		rice chicken,burgers and vegetables
	26-5-2011	6.21	30	12.5	3.4		rice,stew,chicken,pap and vegies
	27-5-2011	6.31	30	12.5	3.2		pizza
	28-5-2011	6.21	30	12.5	3.4		chicken rice and pies
	29-5-2011	6.47	30	12.5	3.2		chicken,rice,mince and fat koek
	30-5-2011	6.43	30	12.5	3.3		chicken,rice spagheti,mince fruits and vegies
	31-5-2011	6.42	60	15	2.9		mash potatoes,rice, mince
	1-6-2011	6.43	60	15	2.9		rice,chicken,pie,fruits n veg
	13-6-2011	6.59	30	9.2	3.2		chicken,rice,vegies
	21-6-2011	6.91	15	7	8	15	peels,rice
	22-6-2011	6.87	15	9	8	16	rice.Veg
	23-6-2011	6.92	20	8	8	17	rice.Pap.
	23-6-2011	6.92	15	8	8	16	veggies,peels
	24-6-2011	6.83	20	8	8	17	pap.Veg
	25-6-2011	6.81	20	10	8	16	bread,veg,rice
	26-6-2011	6.87	20	8	8	17	pasta,rice
	27-6-2011	6.84	25	15	8	16	vegetables.Pap.Rice
	28-6-2011	6.87	50	15	6	17.6	rice, veggies
	10-8-2011						chips ,bread,chicken
	11-8-2011	6.86	20	8	6	24	Salad Bread fruits
	12-8-2011	6.93	20	17		16	bread rice vegetables meat
	13-8-2011	6.91		0		13	
	14-8-2011	6.95	20	17.26		17.1	salad bread tuna beans
	15-8-2011	7.06	16	10.44	7.4	16.9	spaghetti cheese salad chicken
	16-8-2011	7	15	7.64	4.8	19.2	bread Bun rice chicken salad
	17-8-2011	7.01	10	3.22	5.2	20.7	salad Bread Buns meat

H2. Sample of data from Remote Monitoring Study for Phase 2



USER	1.(WC).6.(O).(I)		Weighted BMP	0.144						Stove (m3/hr)	0.73	Power Rating	4.5	kW
Date	pH	Water volume	Food Mass	Burn time	Temperature	Food Description	OLR	Cum. Burn Tim	Cumulativ	Max Theor. Biogas	Biogas Use	Utilisation	OLR	pH (avg)
04-Mar-12														
05-Mar-12														
06-Mar-12	7	4	8	25	18	mixt food waste	1.33							
07-Mar-12	7	5	10	20	20	mixt food waste	1.67							
08-Mar-12	7	8	8	35	16	mainly vegetables	1.33							
09-Mar-12	6.5	9	10	46	17	rice pasta	1.67							
10-Mar-12								2.1	36	8.64	1.53	0.18	1.03	6.88
11-Mar-12														
12-Mar-12	7	9	15	26	14	rice pasta	2.50							
13-Mar-12	7	8	11	35	15	mixt food waste	1.83							
14-Mar-12	6	5	10	10	16	mixt food waste	1.67							
15-Mar-12	8		6		16	rice pasta	1.00							
16-Mar-12	6.5	5	5	37	18	brd meat	0.83							
17-Mar-12								1.8	47	11.28	1.31	0.12	1.34	6.9
18-Mar-12														
19-Mar-12	7	6	12	30	19	mixt food waste	2.00							
20-Mar-12	6	10	15	20	19	eggs samp rice	2.50							
21-Mar-12	7	8	10	45	17	eggs brd	1.67							
22-Mar-12	6	2	8	60	18	mixt food waste	1.33							
23-Mar-12														
24-Mar-12								2.58	45	10.8	1.89	0.17	1.29	6.5
25-Mar-12														
26-Mar-12	7	2	4	20	16	vegetable waste	0.67							
27-Mar-12	7	3	26	25	18	rice samp	4.33							
28-Mar-12	7	5	10	70	19	mixt food waste	1.67							
29-Mar-12	7	4	18	45	17	mixt food waste	3.00							
30-Mar-12	7	8	16	70	18	mixt food waste	2.67							
31-Mar-12								3.83	74	17.76	2.80	0.16	2.11	7
01-Apr-12														
02-Apr-12	7	2	5	45	16	pasta veg	0.83							
03-Apr-12	7	6	4	60	18	mixt food waste	0.67							
04-Apr-12	7	10	15	25	20	pasta rice	2.50							
05-Apr-12	7	2	10	20	14	rice brd	1.67							
06-Apr-12														
07-Apr-12								2.50	34	8.16	1.83	0.22	0.97	7
08-Apr-12														
09-Apr-12	6	4	4	40	16	mixt food waste	0.667							
10-Apr-12	6.5		6	25	16		1.000							
11-Apr-12	7	20	25	55	17		4.167							
12-Apr-12	7	2	14	0	18	brd vegg	2.333							
13-Apr-12	6.5		18	40			3.000							
14-Apr-12								2.667	67.000	16.080	1.947	0.121	1.914	6.600

H3. Data sample from LCF biogas unit showing introduction of simple carbohydrates for Stage 3 of Phase 3



Date	Temperature	Food	Carbs		pH
25-Mar-16	27	1	1	2	6
26-Mar-16	26	1	1	2	5
27-Mar-16	27	1	1	2	6
28-Mar-16	28	2	2	4	
29-Mar-16	29	2	2	4	
30-Mar-16	28	2	2	4	6
31-Mar-16	27	3	3	6	
01-Apr-16	27	3	3	6	6
02-Apr-16	26	3	3	6	
03-Apr-16	26	4	4	8	5
04-Apr-16	26	5	5	10	
05-Apr-16	26	6	6	12	5
06-Apr-16	25	7	7	14	
07-Apr-16	25	8	8	16	
08-Apr-16	24	9	9	18	5
09-Apr-16	25	10	10	20	
10-Apr-16	25	10	10	20	6
11-Apr-16	25	9	11	20	6
12-Apr-16	26	9	11	20	
13-Apr-16	26	9	11	20	
14-Apr-16	27	9	11	20	6
15-Apr-16	27	9	11	20	
16-Apr-16	27	9	11	20	
17-Apr-16	28	8	12	20	6
18-Apr-16	28	8	12	20	5
19-Apr-16	26	8	12	20	
20-Apr-16	26	8	12	20	5
21-Apr-16	26	8	12	20	
22-Apr-16	27	7	13	20	
23-Apr-16	27	7	13	20	6
24-Apr-16	27	7	13	20	
25-Apr-16	27	7	13	20	5
26-Apr-16	27	6	14	20	
27-Apr-16	26	6	14	20	
28-Apr-16	26	6	14	20	5
29-Apr-16	25	6	14	20	
30-Apr-16	27	5	15	20	
01-May-16	27	5	15	20	6
02-May-16	26	5	15	20	
03-May-16	25	5	15	20	5
04-May-16	25	4	16	20	

ANNEXURE: The Energisation Study

This study was Chapter 4 in the original thesis. It has been removed in the revised submission and is presented here as a standalone annexure. All references, apart from one mention in the introduction, have been removed from the core dissertation. As such, this annexure can be read independently.

Introduction

It was under the banner of “Renewable energy for sustainable urban development” by which energisation was redefined in 2010 (Nissing & von Blottnitz, 2010a). With the growing trend of urbanisation, this proved to be seminal work, collating all previous definitions and taking three examples of perceived energisation in South Africa, to redefine the term focusing on socio-economic needs. In this definition, “Sustainable Energisation is the transitional process of progressively meeting primary and early secondary energy service needs of a poor economic subgroup (secondary economy) through the delivery of an enhanced quantity, quality and/or variety of accessible and affordable energy services, enabling the sustainable development of the considered subgroup based on poverty alleviation and economic development as well as the optimisation of the energy service supply network from a lifecycle perspective” (Nissing & von Blottnitz, 2010a). Since this definition, there has been only one actual application using the new definition to improve the quantity, quality and variety of accessible and affordable energy services for a more sustainable development in a rural setting, specifically when finding a replacement for biomass as a cooking fuel (Mungwe *et al.*, 2016). The definition would potentially suit the evaluation of new technologies when evaluating their suitability for deployment in urban settings.

The definition itself was adapted into an economic model which viewed a city as an urban ecosystem with basic inputs and outputs (Nissing & von Blottnitz, 2010b) as a basis for demonstrating energisation. This model is shown below in Figure A1, where it is identified that there is a transfer of technologies, goods and energy between the formal and informal sectors as illustrated. Energisation has been identified as occurring at the nodes of interaction between these sectors.

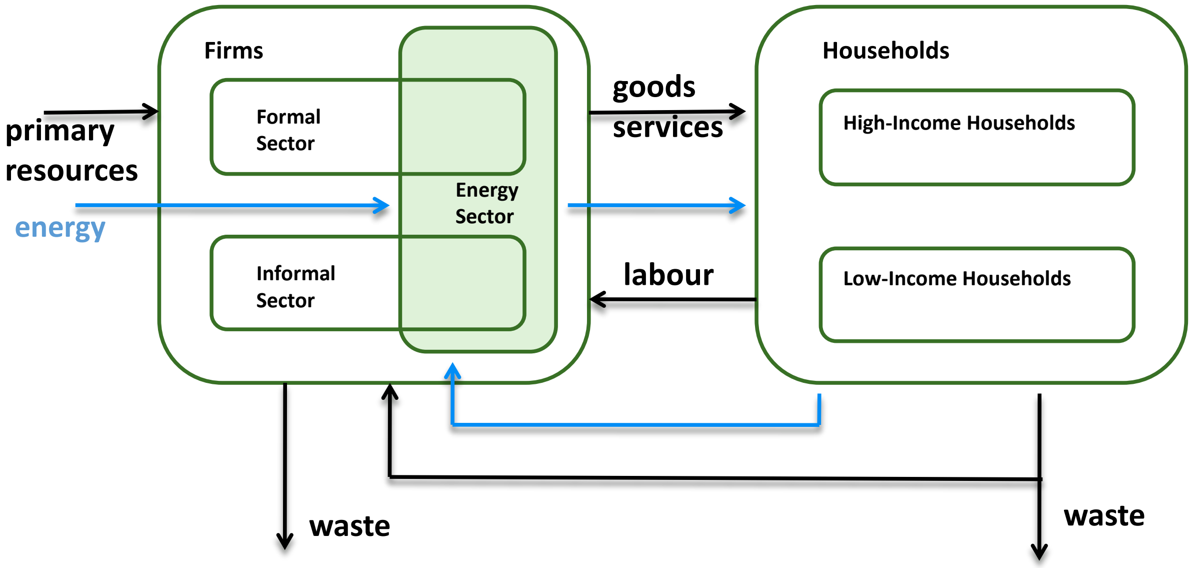


Figure A1. Representation of the economic model, adapted from (Nissing & von Blottnitz, 2010b).

This "model is a free market approach, based on the dynamics of supply and demand, where consumers and producers are the main players" (Nissing & von Blottnitz, 2010a), and would therefore have no restriction on which technologies it can be applied to. This model has then been used in conjunction with an Advanced Local Energy Planning (ALEP) process developed by the International Energy Association (IEA, 2004) to create a tool for energisation. The tool itself comprises of a checklist of 18 aspects of energisation, in a matrix with the energy service supply pathway.

Methodology

The pathway is defined in Table A1 and the matrix is depicted later in Figure A2. With respect to energy production and use itself, the energy supply chain is divided into 7 tiers, however, it must be noted with regard to the energy supply chain, that in some cases, not all of the tiers are applicable, depending on the technology.

Table A1. Superstructure of the energy supply network (Nissing & von Blottnitz, 2010b).

Symbol	Identification
S	Source
s	Primary energy carrier
T	Conversion/distribution technologies
t	Intermediate final energy carrier
D	End-user device
d	Energy service
E	Energy service demands

This structure was then utilised to address 18 aspects against the criteria of Affordability (AF), Accessibility (AS), Poverty Alleviation (PA), Economic Development (ED) and Environmental Protection (EP) as shown in Figure A2. These criteria themselves are identified in the ALEP as the key criteria for sustainable energisation. The level in the energy structure are flagged against the five criteria mentioned here, under each of the 18 aspects.

S	s	T	t	D	d	E	Aspect	AF	AS	PA	ED	EP
X		X					Proximity to end user	X	X			X
X	X	X	X	X	X		Employment	X			X	
X		X					Existing Infrastructure	X	X			X
X	X	X	X	X			Costs	X			X	
X	X	X	X	X			Ease of Processing/Handling	X	X			X
X	X	X	X	X	X		Diversity	X	X	X	X	X
X	X	X	X	X	X		Efficiency	X	X	X	X	X
X		X		X			Waste Management	X	X		X	X
X		X		X			Maintenance	X			X	
	X		X				Traditional Fuels	X		X	X	X
			X	X	X		Bulking	X	X			X
			X	X	X		Health/Safety/Cleanliness			X		
				X	X		Misuse Potential		X	X		
			X	X	X		Substitution	X	X	X	X	X
					X		Passive Measures	X		X	X	X
						X	Priority of Energy Needs			X	X	
					X	X	Hidden Demand			X	X	
						X	Culture & Market Compliance			X	X	

Figure A2. Checklist for energisation, redrawn and adapted (Nissing & von Blottnitz, 2010b).

The matrix can now be used as a tool to evaluate various technologies deemed to be potential energisation technologies. More specifically, each candidate technology could therefore be evaluated against the five categories of energisation under each of the 18 aspects at the relevant levels in the energy supply network to evaluate its suitability for energisation

An example is presented here using the economic illustration (Figure A1). Considering the category of Poverty Alleviation (PA), as highlighted in Figure A5, the relevant aspects are identified. In this case, the relevant aspects would be: Diversity; Efficiency; Traditional fuels; Health, safety and cleanliness; Misuse potential; Substitution; Passive measures; Priority of energy needs; Hidden demand; and Culture and market compliance.

S	s	T	t	D	d	E	Aspect	AF	AS	PA	ED	EP
X		X					Proximity to end user	X	X			X
X	X	X	X	X	X		Employment	X			X	
X		X					Existing Infrastructure	X	X			X
X	X	X	X	X			Costs	X			X	
X	X	X	X	X			Ease of Processing/Handling	X	X			X
X	X	X	X	X	X		Diversity	X	X	X	X	X
X	X	X	X	X	X		Efficiency	X	X	X	X	X
X		X		X			Waste Management	X	X		X	X
X		X		X			Maintenance	X			X	
	X		X				Traditional Fuels	X		X	X	X
			X	X	X		Bulking	X	X			X
			X	X	X		Health/Safety/Cleanliness			X		
				X	X		Misuse Potential		X	X		
			X	X	X		Substitution	X	X	X	X	X
					X		Passive Measures	X		X	X	X
						X	Priority of Energy Needs			X	X	
					X	X	Hidden Demand			X	X	
						X	Culture & Market Compliance			X	X	

Figure A3. Adapted energisation matrix (Nissing & von Blottnitz, 2010b) highlighting Poverty Alleviation (PA).

Each of these criteria are then expanded against the energy supply network as shown in Figure A4, accompanied by a definition for consideration. In this way, each technology is vetted on to understand successes and shortfalls, strengths and considerations for the particular scenario. In the example below, there are three nodes for the criteria of PA under Aspect 12 as shown in Figure A4.

12. Health/Safety/Cleanliness	S	s	T	t	D	d	E
Affordability							
Accessibility							
Poverty Alleviation							
Economic Development							
Environmental Protection							

Description of Aspect 12: Health, safety and cleanliness

These concerns refer to the health impact on the end-user, and thus apply to final energy carriers, end-user devices and energy services. The safe storage of final energy carriers, the safe operation of end-user devices, as well as the safe delivery of energy services are included in the aspect of poverty alleviation. Especially the fire hazard associated with end-user energy supply plays a critical role regarding fires in informal settlements, and annually causes important toll numbers in terms of material and human damage.

Health impacts can be caused by leaking storage devices for final energy carriers, as well as emissions from the conversion processes of the end-user device and the delivered energy service (e.g. indoor air pollution). Evidently, options with lower health impacts should be favoured.

Figure A4. Example of one of the aspects in the energisation matrix, expanded with its definition.

Two studies were undertaken in this framework. Firstly, technologies for a given set of energy demands, specifically in this case for cooking were contrasted. Small-scale biogas was one of these and the other two were efficient wood stoves, and solar cookers. The context of these scenarios was the replacement of biomass (wood), used for brewing, grilling and boiling water with newer methods and technologies. The second comparison is that of the two real biogas installations.

Application of the Toolkit

The energisation framework was applied using the methodology outlined. The first is termed Application A, which is the comparison of small-scale biogas to alternative technologies for the purpose of replacing traditional wood stoves. The second is Application B, which is the comparison of real small-scale biogas units in difference contexts. . Both biogas units are set up at an institutional level. The first is a biogas unit at a university residence (UCT biogas unit) and the second is a biogas unit at a community garden (Abalimi biogas unit).

Application A: Small-scale biogas vs alternative technologies

Using the proposed energy tiers, the supply network is mapped out in Table A2. Biogas engages the energy network on all tiers, while the other two technologies do not, owing to the fact that there is no intermediate energy conversion technology. This is not an indication of small-scale biogas is a more suitable technology, only that it is more complex by virtue of the fact that it converts the energy in waste into a different energy carrier – biogas. However, drawing attention to the fact that each energy tier is expanded, it means that there will be a higher number of nodes when evaluating biogas in the matrix. There will be 178 checkpoints for biogas, and only 119 for the other two technologies.

Table A2. Identification of the energy supply network.

Symbol	Small-scale biogas	Efficient Woodstove	Solar Cooker
S	HH/Stand/Sewage	Timber	Sun
s	Waste	Wood	Sunlight
T	Biogas unit	-	-
t	Biogas	-	-
D	Stove	Stove	Stove
d	Heat	Heat	Heat
E	Cooking	Cooking	Cooking

Each node was noted, and then evaluated as to whether it was relevant or not as well as under which category it was relevant. A high-level overall comparison is shown in Table A3, while each of the categories are tackled in the subsections which follow.

Table A3. Summary of the overall results from energisation node analysis.

	Small-scale biogas	Efficient woodstove	Solar cooker
Nodes	178	119	119
Relevant	99	72	57
Agreements	65 (66%)	53 (74%)	44 (77%)
Flaws	18 (18%)	13 (18%)	4 (7%)

Looking at the number of nodes which were relevant, small-scale biogas generates 99 out of 178 and efficient woodstoves and solar cookers had 72 and 57 out of 119 respectively. From the nodes, which were relevant to each technology, the efficient woodstoves and showed a higher percentage (74% and 77% respectively) of agreements than biogas (66%), and with regard to flaws, the solar cookers came out with the least (4%) while small-scale biogas and efficient woodstoves were tied on 18%. In order to unpack these findings further, the agreements and flaws are unpacked individually under each category.

Affordability

The node analysis under the category of affordability (AF) is presented in Table A4. Here, small-scale biogas exhibits a high percentage of agreement, but not as high as efficient woodstoves. There a low percentage of flaws for small-scale biogas, but the best results again go to efficient woodstoves. The shortcoming with small-scale biogas were identified as high capital and installation costs. A loan agreement may be needed to facilitate the deployment of small-scale biogas. Efficient woodstoves and solar cookers are much cheaper and therefore more affordable, and the only concern for each of these was that they too, may still require micro-financing.

Table A4. Summary of results under affordability from energisation analysis.

	Small-scale biogas	Efficient woodstove	Solar cooker
Nodes	47	30	30
Relevant	41	22	19
Agreements	32 (78%)	20 (90%)	13 (68%)
Flaws	3 (7%)	1 (5%)	1 (5%)

In the operation of biogas, there is a big advantage in that the waste is free. However, if the waste is valorised, there may be a change in the market. Given that biogas may require skilled labour technical support, this would be an added operational cost. Efficient woodstoves on the other hand are implicitly cheaper to operate as they use less fuel, and the energy for solar cooker is free.

Accessibility

For accessibility (AS), small-scale biogas performs the best out of all three technologies as shown in Table A5. This is again because the energy source, waste, is easily accessible. Efficient woodstoves have the same energy source and so accessibility remains unchanged. However, for solar cookers, there is a potential risk of failure to meet primary energy needs on overcast days.

Table A5. Summary of results under accessibility from energisation analysis.

	Small-scale biogas	Efficient woodstove	Solar cooker
Nodes	32	21	21
Relevant	24	15	12
Agreements	18 (75%)	10 (66%)	5 (42%)
Flaws	2 (8%)	2 (13%)	4 (25%)

After the actual installation, accessibility to the stove may be an issue in the informal case. If the biogas unit is installed at an institutional level and there would be access to this facility and the gas, or the stove to meet the energy demand. The other concern with biogas is that it would typically need access to water. If water is not easily available, then the biogas system will not succeed, as has been observed in the rural case. However, in the urban case water is typically more readily available. For the woodstoves, the access to wood in peri-urban forest or as demolition wood would remain unchanged.

Poverty alleviation

The analysis under the criteria of poverty alleviation (PA) is shown in Table A6. All technologies score well with agreements to poverty alleviation. Since all technologies would be used to meet primary energy needs, they would all be better ways of cooking food. The concern with biogas is that it is highly technicaland requires skills for operation making it likely to be unsuitable for the poor and unskilled. Solar cookers and efficient woodstoves would not face such issues.

Table A6. Summary of results under poverty alleviation from energisation analysis.

	Small-scale biogas	**Efficient woodstove**	**Solar cooker**
Nodes	27	20	20
Relevant	15	8	10
Agreements	10 (67%)	7 (88%)	8 (80%)
Flaws	2 (13%)	1 (12%)	1 (1%)

There is one further concern with biogas, and that there may be a cultural acceptance issue when cooking from gas from waste. The market may not accept this technology as readily as it would accept the other two.

Economic development

Biogas would definitely contribute to economic development (ED) giving an adequate agreement as shown in Table A7. There is also the added advantage that biogas serves as a waste management and possibly sanitation option too. If there were to be widespread rollout and technician were needed, there would be an economy created to supply, maintain and provide support for the technology, creating employment.

Table A7. Summary of results under economic development from energisation analysis.

	Small-scale biogas	Efficient woodstove	Solar cooker
Nodes	39	27	27
Relevant	20	17	12
Agreements	12 (60%)	12 (71%)	8 (67%)
Flaws	2 (10%)	0 (0%)	0 (0%)

This would be true for efficient woodstoves and solar cookers too, whereby artisans could be needed to manufacture and possibly maintain the stoves and cookers, and a skills trade could develop. Economically, under market compliance, efficient woodstoves score the best as the market is already established by virtue of the fact that is it the same fuel source.

Environmental protection

Considering environmental protection (EP) as shown in Table A8, small-scale biogas scored the highest because it is renewable energy source which not only saved on transportation but reduces methane emissions which would otherwise come from organic waste degrading in a landfill. The waste management advantage is a strong environmental factor too. The concern with biogas is that if it is misused, and the biogas is not exploited, then the venting of methane into the atmosphere would be environmentally worse. Furthermore, handling of a flammable gas is a health and safety risk.

Table A8. Summary of results under environmental protection from energisation analysis.

	Small-scale biogas	Efficient woodstove	Solar cooker
Nodes	33	21	21
Relevant	30	12	11
Agreements	26 (87%)	6 (50%)	5 (45%)
Flaws	1 (3%)	2 (17%)	0 (0%)

Woodstoves do score well as they inherently have an environmental saving by being more efficient, but it is still not as optimal as biogas or even electricity (resulting in a high incidence of flaws). The waste produced from woodstoves may be toxic if the wood is treated demolition wood, a serious environmental drawback. Solar cookers do not produce waste, but they do not consume waste either. That being said, they have no disadvantages with regard to environmental protection as they are extremely clean technologies.

Application A: Summary and discussions

The findings from the all the criteria are summarised under the headings of the 18 aspects of energisation. These are shown in A9 and colour coded as very positive and high concern. The use of this checklist has highlighted factors which may be very important to energy planners in the development stages of technologies. For example, under Bulking, it may be worthwhile to consider a more medium-scale woodstove or biogas unit to improve efficiencies and reduce costs.

Table A9. Summary of results under criteria headings from energisation analysis.

Aspect	Small-scale biogas	Efficient woodstove	Solar cooker
Proximity to end user	May be an issue if shared	Same as current market	Good
Employment	Definite opportunity	Possibly via artisans	Not really
Existing infrastructure	Needs new infrastructure	Not needed	Not needed
Costs	Initial cost is high	Relatively low	Relatively low
Ease of processing or handling	Some technical skills are needed	Easy	Easy
Diversity	Not highly	Highly	Highly
Efficiency	Depends on scenario	High, built into end-user device, may be low if transport is needed	High w.r.t. energy, low w.r.t. time
Waste management	Very important	Inherently reduces waste	No waste, but also does not address waste
Maintenance	High	Low	Low
Traditional fuels	Replacement	Same fuel	Replacement
Bulking	May be relevant	May be relevant	Not relevant
Health/Safety/Cleanliness	Offers a sanitation solution, but also has a safety risk (handling waste and flammable gas)	Ash may be a problem	Extremely clean and safe
Misuse Potential	Very low	Low (could be used for space heating)	Very low
Substitution	Stove is only end-user device	Normal stoves are cheaper but less efficient	Cooker is the end-user device
Passive Measures	Not known yet	Yes, inherently	Not applicable
Priority of energy needs	Cooking is a primary energy need	Cooking is a primary energy need	Cooking is a primary energy need
Hidden demand	Definitely	Definitely	Definitely
Culture & market compliance	Cultural acceptance with cooking from waste	Good compliance	Cultural is maybe, market is unknown

Reflecting again on the node analyses, the fact that biogas engaged all the energy tiers meant that it was a more complex technology. More complex technologies are not necessary more appropriate. Indeed, it has the added advantage of addressing a waste management challenge, something that the other two technologies do not offer, but the complexity comes at the expense of needed knowledge support/skill in the operation and handling of the gas. It is also a new technology, meaning that there are cultural and market compliance concerns. Finally, the high capital cost of a biogas unit is a major drawback of the technology.

The biggest advantage with efficient woodstoves is that they use the same fuel source giving it good market compliance. However, this is also its biggest drawback because not having a fuel switch means that although there are efficiency savings, any problems associated with the fuel source will still be there, just less pronounced. In this case, health issues associated with burning wood will be reduced, but not removed.

For solar cookers, the cleanest of the technologies, the only issue, but the issue which may be a critical flaw to using the technology, is that it depends largely on an energy source which cannot be ensured. If being used to meet primary energy needs (as it indeed is in this context) then the cooker may simply not work on overcast days and can therefore not be used to replace traditional wood stoves. Additionally, the meal cooking time is typically longer than other technologies. Upon further thought, it is useful to look at the evaluation process as flagging relevance. In this way, the evaluation process evaluated the tool by marking how many of the nodes were in fact relevant. There were indeed instances where the flagged node was not applicable, but certainly no oversights (i.e. a node which should have been marked but wasn't) were encountered.

In summary, biogas is a more complex technology and comes with its own set of challenges and concerns when considering the context of meeting primary energy needs in urban Africa. Skills or knowledge support would be needed to manage operations and health and safety concerns would need to be addressed to ensure operational success. Additionally, there are high costs associated with the technology and a need for existing infrastructure, so deployment in the informal sector may not be an option.

Application B: Context of two small-scale biogas units

Application B was the using the energisation tool kit on two different biogas unit in different settings. The differences in the scenarios are shown in Table A10. Since the energy tiers and the aspect and criteria were the same for both contexts, it was found that the results were almost identical when put through the energisation framework. Further to the summary table it is noteworthy that in the UCT biogas case, the unit was not operated by the end-users of the biogas. However, in the Abalimi biogas case, the community members who operated the unit and used to purchase LPG and therefore saw an immediate savings on LPG by keeping the unit running optimally.

Table A10. Differences between the UCT biogas unit and the Abalimi biogas unit.

	UCT biogas unit	**Abalimi biogas unit**
Type of construction	Prefabricated fixed dome	Constructed inflatable bag
Location	University residence	Community garden
Source of feed	OFMSW	OFMSW
Use of gas	Cooking in canteen	Cooking in kitchen
Use of digestate	None, discharge to sewer	Composting

Returning to the definition of energisation, it is identified that economic opportunities arise when energisation happens. In this regard, it is noteworthy that the in the Abalimi case, excess gas produced was used in a micro-enterprise to fry traditional doughnuts for sale to students at a nearby school. In the energisation framework, this falls under the aspect of hidden demand, and is the clear example of a new economic opportunity.

Conclusions

In the considerations technologies for the energisation of urban Africa, the energisation framework used provided a useful vetting system to flag potential concerns which should be undertaken by energy planners in the concept design phase. From Application A, and in the case of biogas in particular, the complexity of the technology allows it to engage the energy supply network on all tiers, but also creates challenges in the health and safety, cost and cultural acceptance aspects of energisation. It has also been identified that the technical expertise needed to ensure operation is an economic concern, and that there is a need for some formal infrastructure for the biogas unit, so it may not be applicable in the informal African context. That being said, it performs extremely well on the environmental protection category, because it is also a waste management solution, which is one of the 18 aspects.

Efficient woodstoves and solar cookers provide a more direct comparison with each other as they both engage the energy supply network on the same number of tiers. The primary concern with efficient woodstoves is that there is no replacement of traditional fuel with a renewable energy source, only an increase in efficiency, meaning that any disadvantages of the fuel source are only reduced, and not eliminated. Solar cookers, the cleanest of the technologies have one major drawback - the reliability of the energy source. However, this is of high concern and may be a critical concern when considering widespread rollout.

Reflecting on Comparison B, the energisation tool is not useful for comparing different contexts of the same technology. However, observation of each context from the angle of energisation reveals that there was in fact alignment with energisation theory, even though it cannot be directly quantified

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Definitions

The definition of "Energisation"

The following is the revised definition of energisation (Nissing & von Blottnitz, 2010b)

Sustainable Energisation is the transitional process (1) of progressively (2) meeting primary and early secondary energy service needs (3) of a poor economic subgroup (second economy) (4) through the delivery of an enhanced quantity, quality and/or variety (5) of accessible and affordable energy services (6), enabling the sustainable development (7) of the considered subgroup based on poverty alleviation and economic development (8), as well as the optimisation of the energy service supply network from a lifecycle perspective (9).

Key:

(1) The adjective 'transitional' is used, as the described process focuses on the shift from primary to early secondary energy service needs.

(2) The adverb 'progressively' is used in order to emphasise a defined chronological order according to which energy needs have to be met. Although there might be overlaps between primary and secondary energy service needs, it is assumed that generally, primary energy needs will have to be satisfied before secondary energy service needs can be met.

(3) The definition of the terms 'primary and early secondary energy service needs' has been given.

(4) The definition of the target group 'poor economic subgroup (second economy)' is given.

(5) Sustainable energisation takes place when the quantity, quality, and/or variety of energy services delivered are enhanced. This means that at least one of the three elements needs to be enhanced. It is emphasised though that the three elements will never decrease under sustainable energisation. For instance, if the energy carriers fuel wood and cow dung are entirely substituted by the energy carrier electricity, the variety of energy carriers decreases from two to one. However, the variety of energy

services delivered (e.g. cooking and space heating) will remain equal or even increase (e.g. additional refrigeration).

(6) Accessibility and affordability of modern energy carriers have been identified as critical enablers of energisation. In analogy, it is assumed that the terms ‘accessibility’ and ‘affordability’ can be applied to the energy service as such, as the energy carrier is integral part of the energy service supply network.

(7) The term ‘sustainable development’ has been described in the context of sustainable energisation

(8) The terms ‘poverty alleviation’ and ‘economic development’ are defined

(9) The energy service supply network integrates as such the cradle-to-grave approach to the energy service delivered, as it stretches up to the initial resource. However, the lifecycle perspective emphasises that the optimisation of the energy service supply network must account, next to the cradle-to- grave approach, for impacts on all environmental media, as well as a timely component.

The definitions of the "Aspects"

The definitions of each of the aspects are needed to consider each technology in the expanded framework.

Proximity to end-user
This aspect applies to the source, as well as to conversion and distribution technologies. It supports the reduction of transport distances between the different elements, as well as related costs and emissions. Thus, there is an improvement of AF, AS and EP. Note that a source in close proximity to the end-user is generally less prone to global market fluctuations, as it is the case for the fossil resources. Hence, an aspect of security of supply is included. Furthermore, the closer the source or the conversion/distribution technology is to the end-user, the more likely it is that local job/enterprise opportunities are created (see 'Employment').

Employment
This aspect applies to all tiers of the energy service supply network except energy service demand, and focuses specifically on job opportunities for low skilled labour and venture opportunities for small and micro enterprises. For the source, employment can be created regarding the harnessing of the resource. For the primary, intermediate/final energy carriers, job and enterprise opportunities might be available regarding collection, transport, and retail of these commodities. For the conversion/distribution technologies, job and enterprise options might lie in the operation and maintenance sector. For the end-user devices, job and enterprise opportunities might lie in the transport and retail branche. In each case, existing job networks should be respected, and integrated where possible. It is suggested in connection with the existing infrastructure regarding LPG and paraffin, that retail activities could be borne by local Small Medium and Micro Enterprises (SMMEs) (Ward, 2002).

Existing Infrastructure
The integration of existing infrastructure applies for the sources and the conversion/distribution technologies. In an urban area, service infrastructure such as sewage plants exist, which could be integrated as energy sources. Furthermore, existing electricity, gas and heat grids can be integrated for the distribution of intermediate/final energy carriers. For instance, the existing petrol station infrastructure could be used for the distribution of biofuels.

Costs

The cost factor is the key to the final Affordability (AF) of the energy service, and should thus be considered for every element of the energy network, except for the energy service itself and the final energy demand.

Generally, low-cost energy service supply systems should be considered, where harnessing, conversion and distribution include low capital investment and operational costs, while operating with a high technical efficiency, i.a. reducing further costs.

In the context of a developing country, cost estimation for the erection of plants and establishment of energy systems is difficult, as long-term investments are prone to risks (e.g. political stability - see Delany & Varga (2002) and Erb et al. (1996)), there are few cases of precedent, and cost estimations must happen based on proxy factors such as location factors (see e.g. Amigun et al., 2008).

As a rule-of-thumb, it should be aimed at settling labour-intensive industries in developing countries, as a typical characteristic for developing countries is high (unskilled) labour availability and low investment capacity. However, this approach has the danger to oversimplify microeconomic reality. According to van de Ven & van Luijk (1986), labour-intensive industries can be advantageous in underdeveloped countries only if a number of rigorous conditions is satisfied, i.a. a minimum local labour productivity, and a high ratio of indirect/direct workers.

Economic viability for investors is a further issue. While securing affordability for end-users, markets must remain attractive for investors. A means for achieving this goal is the creation of Public-Private Partnerships (PPPs), where financial support from the public side due to its responsibilities towards the population can attract private investment into unattractive markets.

Furthermore, markets unattractive for formal business activity might still bear potentials for informal activities or micro and small enterprises. A conscious coupling of these two business spheres can lead to high synergistic effects. In this context, DME (2003) states that *"In order to provide affordable access and to attract the market and banking sector to service communities with a package of energy services (photovoltaic systems, paraffin, LPG, and renewable alternatives such as gel fuel and solar cookers) sustainable, effective and efficient microcredit schemes and other financial support mechanisms have to be developed and implemented."*

Furthermore, there are financing schemes and subsidies for the different tiers in the energy service supply system in order to render the realisation and implementation economically viable.

In a non-Annexure A country under the Kyoto protocol (e.g. South Africa), the setup of energy service supply measures according to the requirements of the Clean Development Mechanism (CDM) qualifies for extra support based on the trade of Certified Emissions Reductions (CERs) (see e.g. Tyler, 2005). Note that it is more efficient to integrate such requirements in the planning phase of a project, than to upgrade existing projects to fit the requirements. In South Africa, further potential funding for sustainable/renewable energy options is available via Eskom's Demand-Side Management (DSM) fund, or the DME's Renewable Energy Finance and Subsidy Office (REFSO).

Social tariffs for electricity might increase the affordability of electricity. However, a high misuse potential is given (see previous paper, Section 3.1).

Microcredits for the purchase of energy supply technology might be a better option. Micro-financing schemes for the start-up of micro-enterprises are believed to be the best solution regarding economic development from a long-term perspective, as they include the prospect of job creation in the local energy sector (see e.g. Kebir (2003) and E+Co (2004)).

External costs regarding threat to human health and environment should also be considered. However, these issues are discussed elsewhere in this Section.

http://www.dme.gov.za/energy/renew_finnace.stm

The 2006 Nobel Peace Prize was awarded to Dr. Muhammad Yunus and the Grameen Bank "for their efforts to create economic and social development from below" (Nobel Foundation, 2006). Yunus and his bank have meaningfully contributed to the development of the concepts of microcredit and microfinancing (see e.g. Yunus, 1999).

Ease of Processing/Handling

A low technical expenditure regarding the harnessing and processing of energy carriers reduces costs, improves efficiency, decreases health risks and environmental impacts. Moreover, according to the physical state and the harmfulness of the energy carrier, adequate technical measures must be taken regarding the means of transport. By focusing on easily transportable energy carriers, related capital expenditure and potential threats to human health and environment are kept low.

Diversity

The question of diversity applies to all tiers of the energy service supply network, except for the energy service demand. A diverse energy service supply network secures energy service supply firstly in terms of being less vulnerable to global market fluctuations esp. regarding fossil energy carriers, due to the systems capacity to balance instabilities regarding pricing and availability (Heinberg, 2003). Furthermore, a diverse energy supply network is a prerequisite for meeting the diversity of the end-user's energy service demands. Finally, a diverse energy service supply network bears a higher variety of job and venture opportunities, esp. regarding low skilled labour and informal business activities.
A threat is though that the system tends to become less efficient the more diverse it gets after passing a critical point. According to Figure 1 (adapted from Tainter, 1988), prior to point C1/B1, the system can gain efficiency by becoming more diverse. Between points B1/C1 and B2/C2, efficiency gain gradually decreases. After a system passes point B2/C2, efficiency gain becomes negative, and the system becomes vulnerable to collapse. The challenge for planners thus is to render a system as diverse as possible without passing the critical point.
By focusing more specifically on conversion technologies and end-user devices, the option more diverse in its energy products (e.g. Combined heat and power (CHP), cooking stove) should be favoured and recognised as such

Efficiency

From a technical point of view (e.g. thermal and electrical efficiency), sources should be easily harnessed, primary/intermediate energy carriers should be efficiently converted and distributed, and final energy carriers should efficiently be transformed into energy services. The reduction of related emissions, as well as the reduction and reuse of emerging by-product/waste streams contribute to the decrease of malign environmental impacts (see ‘Waste Management’). These considerations could be summarised under the concept of “Cleaner Production” (see e.g. Fijal, 2007).

The ratio of Energy Returned On Energy Invested (EROEI) gives a good approach for measuring the efficiency of specific energy service supply pathways (see e.g. Heinberg, 2003). Effects are not only lower costs, but also a positive environmental impact. It should also be noted that EROEI does not necessarily remain constant over time, but might vary according to the level of depletion of finite sources, or improved conversion efficiency due to technological progress.

As a rule-of-thumb, energy carriers with higher energy content and higher density should be favoured, as they are easier to transport, and allow higher efficiency rates for conversion processes

Waste Management

By reducing/reusing by-products and waste, conversion pathways can be rendered even more efficient. Furthermore, waste and by-products can be used as sources for other energy service supply pathways (see e.g. von Blottnitz et al., 2006). In both cases, waste streams are being diverted from local landfill sites, and environmental impacts as well as related costs are being reduced. Note that here, meaningful business opportunities exist esp. for informal approaches, e.g. paper waste collectors (see Nissing & von Blottnitz, 2007). A good example of this is the success of Zablon Karingi Muthaka (Nairobi, Kenya) who won the Youth Business International Entrepreneur of the Year 2006. Williams (2006) says “Frustrated by the scarcity of official waste disposal sites and the accumulation of rubbish at every street corner of his city, Muthaka spotted a business opportunity and set up Beta Bins Waste Management, a domestic waste collection company. [...] [T]he business proved so successful that its remit has been expanded to include recycling plastics, cottons, paper, bones, metallic products, composite manure and food-stuffs.”

Maintenance

This aspect applies to the source, conversion/distribution technologies, and end-user devices. The ease of maintenance is derived from the nature of the process technology/appliance as such, as well the availability of spare parts and personnel qualified for the task. A simple conversion process or end-user device is in general easier to maintain than a complex one, thus causing lower maintenance costs. On the other hand, the maintenance infrastructure necessary for more complex harnessing/processing technologies and devices bears job and enterprise potentials. These two aspects must be balanced.

Traditional Fuels

A big competitor to primary and intermediate/final energy carriers are traditional fuels such as wood and dung, esp. because of their very low costs. This makes it very difficult for other energy carriers to compete, as affordability is one of the critical enablers for SE. An option would be to subsidise cleaner and safer (final) energy carriers such as electricity. It has been shown that that option has a high risk of misuse (Gaunt, 2003). A further alternative would be to use traditional energy carriers (incl. related job networks) for feeding more efficient/different transformation technologies (e.g. small and large-scale gasifies) and end-user devices (e.g. efficient cook-stoves). By improving the thermal efficiency of such devices from a typical 10% to say 30%, the environmental impact of the collection/harvesting of traditional fuels, (viz. deforestation and lung disease) could be decreased by two-thirds.

Bulking

This aspect applies to intermediate/final energy carriers, as well as energy services. The bulk/grid supply of energy carriers has a favourable effect on affordability due to lower prices, and accessibility due to reduced transport distances. If final energy carriers had to be purchased individually by each end-user at the point of production, transport distances, and related costs and emissions would be much higher. The usage of intermediates such as retailers (e.g. IECs, see previous paper Section 3.2) is an option. The same is applicable for the purchase of end-user devices.

The statement applies for the delivery of energy services as well. For instance, the bulking of transportation such as in public transport systems is more efficient in terms of costs and emissions than individual transportation. However though, end-user behavioural aspects such as convenience play an important role (Howells et al., 2005).

Health, safety and cleanliness

These concerns refer to the health impact on the end-user, and thus apply to final energy carriers, end-user devices and energy services.

The safe storage of final energy carriers, the safe operation of end-user devices, as well as the safe delivery of energy services are included in the aspect of poverty alleviation. Especially the fire hazard associated with end-user energy supply plays a critical role regarding fires in informal settlements, and annually causes important toll numbers in terms of material and human damage (CCT, 2006). Health impacts can be caused by leaking storage devices for final energy carriers, as well as emissions from the conversion processes of the end-user device and the delivered energy service (e.g. indoor air pollution - see von Schirnding et al. (2002)). Evidently, options with lower health impacts should be favoured.

Misuse Potential
Final energy carriers and end-user devices should have a low misuse potential in terms of delivering energy services. As the energy planner has little impact on end-user behaviour, the focus on the delivery of specific energy services via the complex of final energy carrier/end-user device should be integrated in the planning/design stage.

By way of example, the replacement of electric two-plate stoves with gas stoves incl. a bottle of LP gas is reported to have had an immediate effect on the energy use pattern for cooking for affected households (Faniso, 2006). However, the subsidisation (substitution) of end-user appliances such as the distribution of gas stoves and Compact Fluorescent Lighting (CFL) bulbs (see e.g. (Faniso, 2006) and Shlensky (2006)) are believed to be exceptional, as the intervention was motivated by an urgent energy saving need, which would have resulted in much higher costs to Eskom if not met immediately.

Another example is the introduction of Solar Water Heaters (SWHs) as promoted by the bylaw on solar water-heaters in Cape Town (Nielsen & Bengtsson, 2006). By focusing on an end-user device delivering a specific energy service, viz. hot water, the misuse potential has been reduced.

Substitution
This condition applies specifically to final energy carriers, end-user devices and energy services. The level of appropriateness of an alternative energy carrier, end-user device or energy service can be compared to the level of appropriateness of the elements to be replaced, regarding i.a. costs, efficiency, safety, cleanness and environmental impact. If this level is higher than the one of the elements to be replaced, the substitution is advisable. In this context, one can also refer to the concept of “Opportunity Costs”, as being the cost balance of alternatives compared to the option in place (Wesseler, 2007).

Passive Measures
The delivery of energy services can be improved via the integration of passive measures such as house orientation and insulation (see e.g. UNDP, 2000, Chapter 6). Not only does the integration of such measures improve the efficiency of delivered services, but also reduce costs and environmental impacts. Furthermore, the installation of such measures bear job and enterprise opportunities.

Priority of Energy Needs
An energy planner should first identify and prioritise energy service demands as being primary or secondary energy service needs. By doing this, the energy planner can prioritises amongst these energy needs, and assure that the desired effects of poverty alleviation and economic development are achieved. As a rule-of-thumb, energy demand should drive the design of an energy service supply network. Furthermore, misuse potential is being reduced, as energy service demands for less important purposes (e.g. leisure) can then be deprioritised by appropriate measures.

Hidden Demands
Besides the obvious satisfaction of an end-user demand by means of an energy service, there might be other demands that could be satisfied simultaneously. The energy planner must identify these hidden demands in order to render the energy service delivery as efficient as possible, and optimise the impact of SE

Culture & Market Compliance
The specification of energy services should be consistent with the cultural values of the concerned population groups, as well as the market requirements in the case of energy service demands for commercial purposes. In the case of cooking for commercial purposes (see e.g. meat *braaing*), a market demand besides the cooked food is the flavour of burned wood, thus having an impact on the final energy carrier (see previous paper, Section 3.3). The entirety of the aspects concerning culture & market compliance must be understood when identifying energy demands.

An example of an “Application”.

Thus small-sale biogas is considered under the aspect of proximity to end user as follows. The flags on the categories are Affordability, Accessibility and Environmental Protection. The flags on the energy tiers are Source and Primary conversion technology. So, each node is considered.

1. Proximity to end user	**S**	**s**	**T**	**t**	**D**	**d**	**E**
Affordability	very cheap (waste)		ok				
Accessibility	may be an issue		ok				
Poverty Alleviation							
Economic Development							
Environmental Protection	high						

Relevancies, agreements and flaws are flagged. Here, it is noted that the source (waste) has a strong agreement under affordability, as it is free, and is very close to the user.