EVALUATING THE SUSTAINABLE POTENTIAL OF BIOGAS GENERATION IN SOUTH AFRICA

By

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: March 2018

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DEDICATION

I am grateful for this opportunity, to be able to dedicate this thesis to my beloved mother and father, for their unconditional devotion, guidance, love and support.

SUMMARY

With a global movement towards a more sustainable way of living, the two most noteworthy hurdles to overcome in the quest for sustainable development are the unsustainable management of waste and availability of clean energy. This study investigates the potential of biogas generation in South Africa, referring specifically to its potential as a sustainable agricultural practice and evaluates the process of anaerobic digestion and biogas utilisation as a strategy to improve the country's performance measured against two determinants of sustainability, namely: 1) the provision of a clean and affordable energy supply and 2), organic waste management.

A literature review was conducted to create a contextual framework against which biogas generation potential can be evaluated. The status of the global biogas industry and how South Africa compares to the world, not only in terms of the extent of the industry, but also in terms of its sustainability performance as a country, is outlined.

The status, as well as the specific challenges and opportunities that are present in the South African biogas industry, were further researched by means of face-to-face semi-structured interviews with major role-players, among others representatives of the South African Biogas Industry Association (SABIA) and GreenCape. This investigation indicated an interest in the development of medium and commercial-scale biogas digesters which could be attributed to opportunities that the biogas industry offer in terms of job creation, energy provision, carbon mitigation, organic fertiliser production and waste management. The study confirmed that the South African industry is currently faced with numerous challenges in terms of renewable energy generation and supply, e.g. lack of government support, financial commitments involved in its development, skills shortages, ethical challenges, limited water resources and sustainable access to waste as a biomass source. However, innovative enablers do exist and can promote the growth of the industry. These findings support the notion that biogas generation can contribute significantly to sustainable development in South Africa.

By applying enabling factors such as streamlining EIA processes and licencing requirements and creating a market for surplus energy generated, biogas generation can provide tax relief through the anticipated implementation of carbon tax; create innovative solutions for waste management and the organic fertiliser industry, while delivering ecosystem services such as

carbon sequestration in soils and improved water and soil quality and ultimately, an increase in food production. In addition, by integrating waste management and renewable energy technologies, biogas generation could potentially contribute to the alleviation of poverty and the well-being of society.

The rationale of the third part of the study was to establish the potential of farm-scale biogas generation as a sustainable agricultural practice in South Africa. Findings are based on interaction with two groups of farmers – 1) those without biogas digesters and 2), those with biogas digesters. Purposive data collection was conducted through two self-administered electronic surveys that were sent to farmers in both groups. The quantitative data obtained was further supported and clarified through personal conversations with participants in both surveys and measured against what is defined in this paper as sustainability: economic potential, social potential and environmental potential – the three pillars of sustainability. For this reason each of these categories were defined and the applicable factors that may impact these categories, described.

The fourth part of the study aimed to identify the farm-scale biogas production system with the most sustainable potential in an agricultural application that can benefit the pursuit of a more sustainable future under local conditions. However, it was established that the numerous variables in the South African biogas generation scenario complicate implementation and that implementation should be site-specific to be feasible. A generic model was developed to enable the evaluation of the sustainable potential of a specific digester type at a specific site, taking all the variables into account. The model, a decision-making tool, is based on the scoring of the three determinants of sustainability namely environmental, social and economic according to a set of defining factors. Based on literature and local expertise, collected through interviews, a comparison of the characteristics of digester types with agricultural requirements enabled the identification of the Continuously Stirred Tank Reactor (CSTR) digester as the type that could show the most potential when implemented as a sustainable solution to address energy poverty, the rising costs of electricity and waste management demands. The validation of the sustainable potential of the CSTR digester type through further studies is recommended.

Although numerous existing challenges hinder the potential of biogas generation in South Africa, the study concludes that biogas generation has potential to contribute to sustainable agriculture and that it presents a substantial opportunity to promote sustainability and simultaneously address prominent challenges like waste removal, energy supply, water recycling and skills development.

OPSOMMING

In die wêreldwye strewe na ‘n meer volhoubare lewenswyse is daar twee struikeblokke van belang – onvolhoubare afvalbestuur en die voorsiening van energie. Hierdie studie ondersoek die potensiaal van biogasopwekking in Suid-Afrika, met spesifieke verwysing na die potensiaal om as ‘n volhoubare landboupraktyk geïmplementeer te word en evalueer die proses van anaerobiese vertering en biogasgebruik as ‘n strategie om die land se prestasie in volhoubaarheid te verbeter, met spesifieke verwysig na 1) die voorsiening van skoon en bekostigbare energie en 2), organiese afvalbestuur.

‘n Literatuurstudie is geloods as agtergrond waarteen die potensiaal van biogasopwekking ge-evalueer kan word. Die status van die wêreldwye biogasindustrie en ook hoe Suid-Afrika vergelyk met die res van die wêreld, nie net in terme van die omvang van die industrie nie, maar ook in terme van sy volhoubaarheidprestasie, word bespreek.

Die status, sowel as die spesifieke uitdagings en geleenthede wat die biogasindustrie in Suid-Afrika bied, is verder ondersoek aan die hand van aangesig-tot-aangesig semi-gestruktureerde onderhoude met sleutelrolspelers in die industrie – onder wie verteenwoordigers van SABIA (South African Biogas Industry Association) en GreenCape. Hierdie ondersoek het aangedui dat die belangstelling wat heers in die ontwikkeling van medium tot groot (kommersiële) biogas reaktors toegeskryf kan word aan die geleenthede wat dit bied in terme van werkskepping, kragvoorsiening, koolstofmitigasie, produksie van organiese bemesting en bestuur van afval. Die studie het bevind dat die Suid-Afrikaanse biogasindustrie deur verskeie uitdagings in die gesig gestaar word, soos die opwekking en voorsiening van hernubare energie, tekort aan regeringsteun, finansiële vereistes tydens ontwikkeling, vaardigheidstekorte, etiese uitdagings, beperkte waterbronne en toegang tot afval as voermeganisme, maar dat daar innoverende meganismes bestaan om die groei van die bedryf te kan stimuleer. Dit bevestig die aanname dat biogasopwekking ‘n sleutelbydrae kan lewer tot volhoubare ontwikkeling in Suid-Afrika. Deur hierdie innoverings toe te pas – soos die vereenvoudiging van die omgewingsimpakproses en lisensiëringsvereistes asook die skep van ‘n afsetmark vir oortollige energie wat opgewek word – kan biogasproduksie belastingsverligting meebring deur die verwagte implementering van koolstofbelasting, meer doeltreffende afvalbestuur en die produksie van organiese bemesting terwyl ekostelseldienste gelewer soos koolstofsekwestrasie in grond en verhoogde water- en grondkwaliteit wat

uiteindelik kan lei tot ‘n verhoging in voedselproduksie. Hierbenewens kan biogasproduksie ook moontlik bydra tot die verligting van armoede en die welsyn van gemeenskappe deur afvalbestuur en die opwekking van hernubare energie te integreer.

Die mikpunt met die derde gedeelte van die studie was om die potensiaal van biogasopwekking op plase as ‘n volhoubare landboupraktyk te evalueer. Bevindinge is gebaseer op interaksie met twee groepe boere – 1) diegene wat nie biogasreaktors het nie en 2), diegene wat biogasreaktors het. Doelgerigte data is versamel met die hulp van selftoegepaste opnames wat elektronies aan boere in albei groepe gestuur is. Inligting ingewin is verder aangevul deur persoonlike gesprekke met deelnemers aan albei opnames en gemeet teen dit wat in die artikel gedefineer word as volhoubaarheid, ekonomiese potensiaal, sosiale potensiaal en omgewingspotensiaal – die drie bakens van volhoubaarheid. Ten einde dit te kon doen, is elk van hierdie kategorieë gedefinieër en die faktore wat elkeen van hierdie kategorieë bepaal, uiteengesit.

Die vierde gedeelte van die studie het ten doel gehad om die biogasreaktor met die meeste potensiaal vir toegepassing in die landbousektor en wat dus Suid-Afrika se visie in terme van ‘n volhoubare toekoms kan bevoordeel, te identifiseer. Daar is egter vasgestel dat die groot verskeidenheid veranderlikes in die Suid-Afrikaanse biogas scenario die implementering van ‘n enkele tipe biogasreaktor as ooglopende oplossing verhinder. Dit het aanleiding gegee tot die ontwikkeling van ‘n generiese model wat as besluitnemingsmeganisme gebruik kan word om die evaluering van die volhoubare potensiaal van spesifieke tipes biogasreaktors op ‘n spesifieke terrein moontlik maak. Tweedens, gebaseer op literatuur as ook onderhoude met kenners in die veld, is vergelykings getref tussen die eienskappe van bestaande biogasreaktors en hoe dit antwoord in die vereistes van die landbousektor. Op grond daarvan is die ‘Continuously Stirred Tank Reactor’ (CSTR) geïdentifiseer as die reaktortipe wat die meeste potensiaal het om in die landbou geïmplementeer te word as volhoubare landboupraktyk om die voorsiening van ‘n betroubare en bekostigbare bron van krag en en sinvolle afvalbestuur moontlik te maak. Daar word dus voorgestel dat die volhoubare potensiaal van die CSTR reaktor tipe gebruik word vir die evaluasie van die geldigheid/validasie van die generiese model vir implementasie van hierdie biogasreaktor tipe volgens die behoeftes van ‘n spesifieke terein.

Die gevolgtrekking was dat, selfs in die lig van die verskeie struikelblokke wat bestaan, biogasopwekking in die Suid-Afrikaanse landbousektorvolhoubare potensiaal het, en ook sodoende ‘n geleentheid bied op volhoubaarheid sowel as om prominente uitdagings aan te spreek soos afvalverwydering, enegie voorsiening, watersirkulering en die ontwikkelling van vaardighede.

EXPLANATION OF STYLE

This thesis is a compilation of chapters, starting with a literature review, followed by three research papers. Each paper is prepared as a scientific paper for submission to *South African Journal for Plant and Soil*. Selective repetition or duplication between papers is therefore unavoidable.

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GENERAL INTRODUCTION

Sustainability is an important concept in this study, as the potential of biogas utilisation is evaluated against the principles of sustainability, namely economic, social and environmental sustainability (DEA 2008, Nahman *et al.* 2009, Kuhlman and Farrington 2010, Morelli 2011, GreenCape 2017b, Uwosh.edu 2017).Currently the world faces various challenges in terms of sustainable living (UN 1987, UN 2015, UNDP 2017). With the global movement towards a more sustainable way of life, the unsustainable management of waste and availability of clean energy has been identified as significant hurdles that have to be overcome (UN 1987, UN 2015, SAGEN and SABIA 2016, CRSES 2017, UNDP 2017).

Even though South Africa has identified a vision and strategies to re-orientate its development path to one that is more sustainable, the country fares extremely poorly in comparison to other countries and is named as the worst performer out of the 21 countries in sub-Saharan Africa (DEA 2008, Emerson *et al.* 2012, DEA 2013, EPI 2014, ESI 2017, SEDAC 2017). South Africa's sustainability policy imperatives are further driven by indices such as the Environmental Sustainability Index (ESI) and Environmental Performance Index (EPI) (EPI 2014, ESI 2017) and its signatory commitments to the Kyoto Protocol and the Paris Agreement (NT 2014). Its poor environmental performance is, however, ascribed to the way in which the country's water shortages are managed, its contribution to air pollution and climate change, as well as poor public health and agricultural practices.

Energy policies implemented in South Africa are required to address sustainability by mitigating the effects of climate change, which simultaneously provides extra motivation for the Department of Energy to include technologies such as gas, biomass, solar, thermal and wind resources to meet South Africa's future electricity needs (DoE 2016, DEA 2017). This creates substantial opportunity for biogas generation, as biogas does what few other renewable energy technologies do, which is to integrate waste management and energy technology (Biogas 2013, Bachmann 2015, SAGEN and SABIA 2016, GreenCape 2017c). This creates a promising pathway towards achieving sustainable development, by ultimately reducing methane (CH_4) and carbon dioxide (CO_2), while incorporating the social dynamics and requirements of a developing country by overcoming energy poverty, creating jobs, supplying organic fertiliser, improving waste management, saving on energy and waste disposal costs and creating new business incentives (Smith 2011, Biogas 2013, NERSA 2013, SAGEN and SABIA 2016, GreenCape 2017a, GreenCape 2017c, Tiepelt 2017).

Biogas generation may especially suitable as a sustainable agricultural solution to the challenges faced by the developing world, and specifically the agricultural community in South Africa, but the slow uptake of this technology both rurally and commercially compared to other developed and developing countries, is attributed to numerous challenges (Smith 2011, Abbasi 2012, Amigun *et al*. 2012, Biogas 2013, Griffiths 2013, SAAEA 2016, SAGEN and SABIA 2016, GreenCape 2016, GreenCape 2017a, GreenCape 2017c, Tiepelt 2017).

The first objective of this study was to evaluate the potential of the biogas digester industry against the principles of sustainability, taking into account the status, challenges and opportunities that the industry presents. For this purpose, face-to-face semi-structured interviews (Babbie and Mouton 2001) were conducted with, among others, representatives of the South African Biogas Industry Association and GreenCape, a non-profit organisation that drives the widespread adoption of economically viable green economy solutions from the Western Cape. Obtaining renewable energy through biogas generation proved to be particularly complex and the South African industry is currently faced with numerous challenges in terms of renewable energy generation and supply, due to a lack of government support, financial commitments involved in its development, skills shortages, ethical challenges, limited water resources and sustainable access to waste as a biomass source (Terreblanche 2002, Smith 2011, AltGen, GIZ, SAGEN and GreenCape 2014, Ruffini 2014, Torquati *et al.* 2014, GIZ-SAGEN 2015, Creamer 2016, GreenCape 2016, SAGEN and SABIA 2016, GreenCape 2017a, GreenCape 2017b, GreenCape 2017c, Tiepelt 2017). These findings created the opportunity to identify, investigate and recommend certain enabling factors that can be pursued to further develop and promote the sustainable potential of the industry. This includes streamlining legislation and licencing requirements, enabling the off-take of energy generated through various means, providing adequate financial support through grants and rebates, and creating opportunities for education and skills transfer (AltGen, GIZ, SAGEN and GreenCape 2014, GIZ-SAGEN 2015, SAGEN and SABIA 2016, GreenCape 2017c, Tiepelt 2017).

The second objective was to establish the potential of farm-scale biogas generation as a sustainable agricultural practice in South Africa by investigating the reasons that may contribute to the decisions of farmers either to invest in biogas digesters, or not to invest.

Self-administered electronic surveys (Babbie and Mouton 2001) were sent to the farmers for data collection. The study analysed the understanding that farmers share about sustainability and biogas generation; the effects of climate change on agricultural practices; the major hindrances, challenges, opportunities and benefits facing biogas digesters in the agricultural sector; the applicability of biogas digesters installed on farms and the reasons for either implementation or no implementation of biogas digesters.

The third objective was to create a method by which the digester type applicable to farm-scale digestion that could deliver the best results as a sustainable agricultural practice, can be identified. However, the numerous variables in the South African scenario complicate implementation and it is apparent that implementation locally should be site-specific to be sustainably feasible (Lutge 2010, Biogas 2013, GreenCape 2017a, GreenCape 2017c, Mutungwazi *et al.* 2017, Tiepelt 2017). A proposed generic model was developed as a decision-making tool to enable the evaluation of the sustainable potential of a specific digester type at a specific site, taking all the variables into account. Further, by considering the characteristics of various agricultural digester models and comparing it to the needs of the farming sector, a specific digester type was identified as having the most potential to be implemented as a sustainable solution. This digester type was drafted and described as a guideline for implementation at farm-scale.

In general, this thesis investigated the application of biogas generation in an agricultural context. This was achieved by determining the country's vision and commitment to sustainable development and the opportunities that agricultural sector, together with biogas generation, present. Its applicability in the agricultural sector was researched by consultation with developers, development agencies and farmers. This information was used to propose a decision-making tool (generic model) that will enable the evaluation of biogas digesters for potential implementation on farm scale.

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LITERATURE REVIEW: OVERVIEW OF THE STATUS OF BIOGAS GENERATION, WITH REFERENCE TO ITS SUSTAINABLE POTENTIAL IN SOUTH AFRICA

1.0 Introduction

Sustainability is an important concept in this study, as the potential of biogas utilisation is evaluated against the principles of sustainability. With a global movement to a more sustainable way of life, the two most noteworthy hurdles to overcome in the quest for sustainable development are: 1) the unsustainable management of waste and 2) the availability of clean energy (SAGEN and SABIA 2016, CRSES 2017). This review will refer to South Africa's demand for energy and waste management, and how these factors impact on the sustainable potential of biogas utilisation.

Sustainability as a concept is discussed as defined in the National Framework for Sustainable Development (NFSD) and the approach of the Department of Environmental Affairs (DEA), including the Environmental Sustainability Index (ESI), The Environmental Performance Index (EPI) and the strategy for sustainability in South Africa. The potential of biogas utilisation could impact all three pillars of sustainability i.e. environmental, social and economic, and for this reason it is found appropriate to define sustainability as applicable to this study by referring to different definitions in literature (UN 1987, DEA 2008, Kuhlman *et al.* 2010, Morelli 2011, EPI 2014, Uwosh.edu 2017).

In this review, sustainability is defined as: "*The process of utilising and living within the limits of available physical, natural and social resources in ways that promote social, ecological and economic sustainability all at the same time, while allowing the living systems in which humans are rooted to flourish in perpetuity*" (UN 1987, Nahman 2009). The process of biogas generation is seen as a promising pathway towards achieving sustainable development, ultimately reducing methane (CH_4) and carbon dioxide (CO_2), while incorporating the social dynamics and requirements of a developing country; promoting ways to reduce energy costs, provide waste management solutions and produce organic fertiliser for own use or as an additional source of income (Biogas 2013).

1.1 Global biogas digester industry

Internationally biogas has substantial potential as a renewable energy source. Regarded as the so-called oxygen of an economy, energy is regarded as an undisputed driver of economic development and has a key role in the socio-economic progress of countries (World Economic Forum 2012). It is estimated that biogas could be a primary source of energy covering up to 6% of the global energy supply, or a quarter of the present-day utilisation of gas fossil CH_4 (natural) gas (Holm-Nielsen *et al*. 2007).

Table 1: The estimated cumulative total number of biogas digester plants of all sizes and types in the European Union, Asia and Africa.

Region	**Estimated total biogas digester plants**	**Year**	**Source**
European Union	17 376	2015	EBA 2017
Asia	39 979 675	2012	Surendra *et al.* 2014
Africa	24 990	2012	Surendra *et al.* 2014

The global biogas plant market stood at 56 276 units in 2015 and expected to reach 59 697 by the end of 2016 (Trancparencymarketreseach 2017). Table 1 indicates that Asia has the most installed biogas digesters and that Africa and the EU are on a similar footing. The majority of biogas digesters installed in Asia and Africa are however small-scale/domestic biogas digesters, while the installations in the EU are on a larger/commercial scale (Zhu 2006, Smith 2011, Bond and Templeton 2011, Amigun *et al*. 2012). Surendra *et al.* (2014) estimated that there were about 39.9 million biogas digesters in Asia in 2012. Therefore it can be accepted that when referring to the estimated 2016 global total of 59 697, it refers to larger scale biogas plants.

Europe is regarded as a leader in the field, with a total of 17 376 biogas plants and 459 bio-methane plants active in the European Union in 2015 (EBA 2017) generating a total amount of 60,6 TWh electricity which corresponds to the annual electricity usage of some 13,9 million European households (EBA 2017).

While Holm-Nielsen *et al*. 2007 estimated that biogas from wet organic matter (OM) such as food waste, animal manure and crop by-products, could supply at least one quarter of all future bioenergy, Abbasi (2012) predicted that by 2020 farms and large co-digestion biogas plants that are part of farming and food-processing structures, will produce the largest volume of biogas.

From these arguments it is clear that the technologies are available and ready for South Africa to take advantage of. In addition to the availability of relevant technologies, there are a number of incentives available locally and globally, such as carbon tax incentives (NT 2013), which make farm-scale biogas plants a very attractive option for the agricultural sector looking to reduce their carbon (C) footprint and save on electricity bills (Griffiths 2013, Scharfy *et al.* 2017), also supported in findings of paper 1.

A study in 2012 by Barnhart compared three different types of biogas development scales in Nepal, the United States and Sweden. It was found that in Nepal, biogas production mainly supplies rural household energy, while in the United States biogas is produced on an industrial-scale at waste management applications, with the generated energy being either used on site or fed into a regional power grid (Barnhart 2012). In Sweden, biogas forms part of a new energy strategy enabling municipalities to function energy independent and fossil fuel free. These examples show how a renewable energy technology can be adapted and used across scale and cultural/social contexts, in urban or rural environments and extending from developing to developed countries (Barnhart 2012).

The global biogas market is likely to be further developed by increased support shown by private bodies and the government to biogas plant owners, in terms of setting up of sufficient regulations and financial incentives. The market is also being influenced by the constructive contribution that fully functional biogas plants can make to reduce the volume of disposed waste into landfills (Trancparencymarketreseach 2017). However, the growth rate could be hindered by the lack of feasible waste segregation systems (Transparencymarketresearch 2017). This could restrict the availability of feedstock to biogas plants, discouraging several new entrants into this competitive market (Biogas 2013).

It is expected that the biogas market will remain positive within the forecast period from 2016 to 2024 with a compound annual growth rate (CAGR) of 6,5% (Trancparencymarketreseach 2017), providing a constant rate of return over this time (Investopedia 2017). It is further predicted that this market’s volume will reach 86 964 biogas plants at the end of 2022, which means that more than 30 000 units are expected to be established within this period (Trancparencymarketreseach 2017).

1.2 Developing versus developed continents

1.2.1 European Union, with specific reference to Germany

Internationally the use of biogas as an energy source is not new (Griffiths 2013). In recent years, the impact of low-carbon, renewable bioenergy applications on a country's national energy sources have become increasingly important (Cherubini and Strømman, 2011).

In the European Union, the interest in bioenergy originates from the necessity to promote the use of renewable energy sources to achieve objectives such as: (a) a reduction in dependence on fossil fuels; (b) a reduction in emissions responsible for climate change; (c) the development of new source of income for the agro-forestry sector; and (d) effective disposal of wastes (Cherubini and Strømman, 2011).

Biogas in Europe is produced as so-called landfill gas during anaerobic degradation at landfills, at large-scale industrial digesters used for sewage sludge, as well as in small-scale digesters on individual farms (EU Handbook 2012).

According to the European Biogas Association's statistical report (6th addition), the biogas sector has been growing steadily with the number of biogas plants growing threefold in only six successive years, with significant increases in the United Kingdom (with 77 additional plants showing 17 % growth), Belgium (with 20 additional plants showing 11 % growth) and the Netherlands (with 16 additional plants showing 6 % growth) (EBA 2017).

This is mainly due to new regulations that place restrictions on waste management and the initiation of support schemes and financial incentives for renewable energy technology such as government incentives for feed-in tariffs that have been implemented in many European countries (EU Handbook 2012, GreenCape 2017a). In addition, farmers are encouraged by the potential to earn additional income by planting energy crops and the opportunity to produce electricity and/or heat from biogas while continuing with their traditional agricultural activities (EU Handbook 2012, Torquati *et al.* 2014). These measures are aimed at increasing renewable energy production, while enabling farm estates to reduce their energy dependence and develop their income streams in the event of falling cereal, milk or meat prices (EU Handbook 2012).

Waste water treatment works (WWTWs) are challenged with their requirement for optimal energy usage and nutrient recycling (Bachman 2015). To meet such requirements, the Netherlands has implemented an innovative concept, the NEW (nutrient, energy and water) factory. The NEW factory concept suggests that wastewater should be regarded as a resource of energy, nutrients and clean water rather a waste product. A roadmap has been set up on how to achieve the goals of the NEW Factory by 2030 (Roeleveld *et al.* 2010).

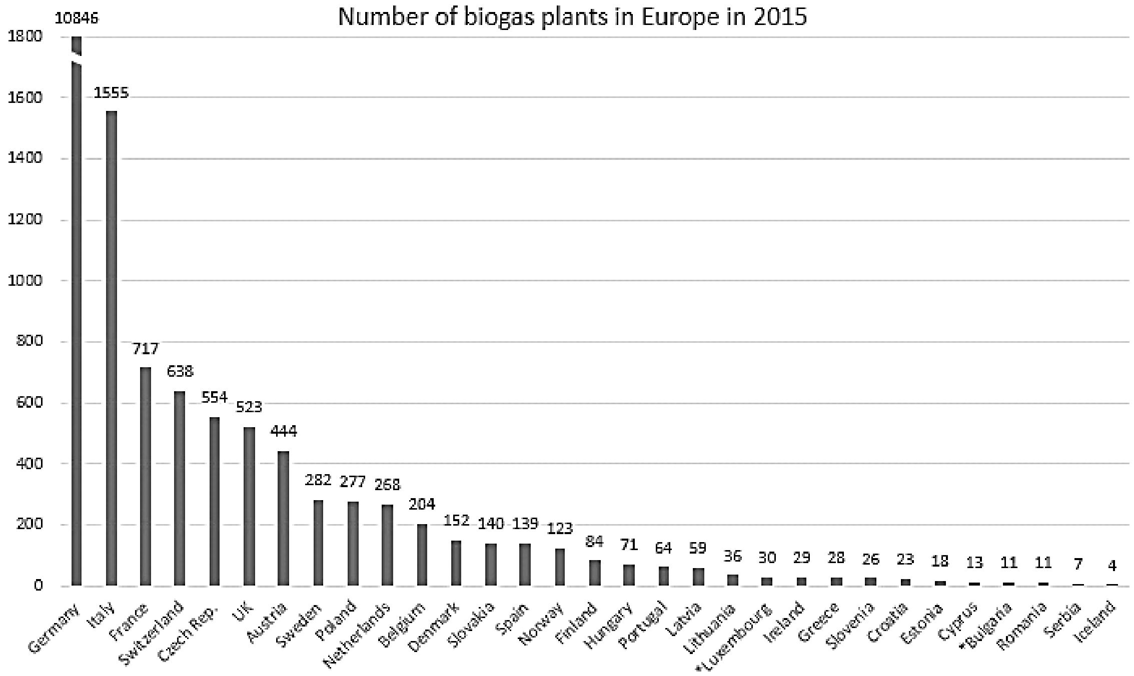

Figure 1: Illustration of the amount of biogas plants in Europe per country in 2015. (Source: EBA 2017).

Germany is one of the more prolific and successful implementers of biogas-power projects. Almost 13 % of all renewable power generated in Germany can be attributed to medium to large-scale biogas plants (Griffiths 2013). The German Biogas Association (GBA) estimated that there were 7 320 electricity-producing biogas plants throughout Germany in 2011 and predicted its growth to 7 874 in 2013 (GBA 2013). At the time it was estimated that Germany was building a commercial digester roughly every eight hours. In 2011, the estimated combined capacity of these plants was 2 997 MW, and in 2014 the estimated capacity reached over 9 600 MW (GBA 2013, Ruffini 2014).

A significant factor contributing to the successful implementation of these projects is support from the German government. The Renewable Energy Sources Act of 2000 guarantees compensation for electricity produced by a renewable energy plant for 20 years (Griffiths 2013). A further reason for Germany's success is its excellent infrastructure for producing as well as distributing and using biogas. A sophisticated road and rail network allows effective and reliable feedstock deliveries to biogas installations, and a well-established bio-waste segregation and collecting system enables the further development of the substantial bio-waste potential. A dense and country-wide electricity grid of approximately 1,7 million km in length is available for electricity feed-in. Further extensions of this grid capacity are planned for the short term as some remote areas have limited capacities for additional electricity feed-in. A natural gas grid of more than 443 000 km is also available for bio-methane feed-in (EU Handbook 2012).

Furthermore the German government announced an excellent support scheme with fixed feed-in tariffs for different feedstocks, guaranteed access to the well-regulated grid and long-term payment options. The feed-in law is regularly revised to keep the tariffs market-related (EU Handbook 2012).

1.2.2 Asia

The Chinese have been using biogas from agricultural and household waste for cooking since 1929 (Chen *et al.* 2012). The last 30 years have seen the introduction of biogas to power plants supplying from 20 kW up to 600 kW. Large agricultural biogas plants are a more recent trend with only 3 % of the biogas plants installed used for power generation. Notable biogas-to-power plants include a plant in Shandong province which utilises 500 tonnes of chicken manure to generate 60 000 kWh of power daily, one in Meng Niu which treats manure from dairy cows to generate 18 000 kWh per day and a project in Beijing which digests manure and generates 38 000 kWh power per day (Chen *et al.* 2012).

Table 2: The amount of biogas plants fitted in Asia according to Ghimire 2013 and Surendra *et al.* 2014.

Country	**Year of initiation**	**Total number of plants fitted until 2009 (Ghimire 2013)**	**Total number of plants fitted until 2012 (Surendra *et al.* 2014)**
China	1974	27 000 000	35 000 000
India	1970s	4 000 000	4 500 000
Nepal	1992	205 762	268 464
Vietnam	2003	75 820	152 349
Bangladesh	2006	10 019	26 311
Cambodia	2006	6 402	19 173
Laos PDR	2006	1 020	2 888
Indonesia	2009	50	7 835
Pakistan	2009	100	2 324
Bhutan	2011	-	265
Total		**31 299 173**	**39 979 675**

1.2.3 Africa

While not as common as in Europe and Asia, domestic biogas digesters have been installed in South Africa and Kenya since the 1950s. The most widely used biogas model is that of small-scale biogas digester using household and domestic animal waste. Most African countries show a low level of technological development with South Africa regarded as more advanced (Amigun *et al.* 2012).

Griffiths (2013) estimated that by the end of 2013 there were as few as 150 biogas digesters in South Africa. According to Ruffini (2014), there were some 200 registered biogas digesters in the country by the end of 2014. Mark Tiepelt, former chairman of the South African Biogas Association (SABIA) however, stated at the South African International Renewable Energy Conference (SAIREC) in 2015 that there are around 700 digesters in the whole of South Africa and that approximately 40 % are at existing waste water treatment works, 50 % are small-scale domestic/rural digesters, and only around 10 % are commercial installations (SAIREC 2015). GreenCape (2017c) estimated that there are currently 500 digesters in South Africa (200 digesters at WWTW; 300 used for other purposes). These numbers lag far behind other African countries based on the findings of Ghimere (2013) and Surendra *et al.* (2014) as listed in the table 3, with Kenya (6 749), Ethiopia (5 011) and Tanzania (4 980) leading the way.

Table 3: The amount of biogas plants fitted in selected African countries (excluding South Africa) measured by two studies Ghimire 2013 and Surendra *et al.* 2014.

Country	**Year of initiation**	**Total number of plants fitted until 2009 (Ghimire 2013)**	**Total number of plants fitted until 2012 (Surendra *et al.* 2014)**
Rwanda	2007	434	2 619
Ethiopia	2008	128	5 011
Tanzania	2008	3	4 980
Kenya	2009	106	6 749
Uganda	2009	40	3 083
Burkina Faso	2009	1	2 013
Cameroon	2009	23	159
Benin	2010	-	42
Senegal	2010	-	334
Total		**735**	**24 990**

Studies have also shown that in sub-Saharan Africa half a billion people do not have access to electricity in their homes. These households rely on biomass such as wood, animal waste and agricultural residues to meet their basic needs for lighting, heating and cooking (Brown 2006, Amigun *et al.* 2012, Msibi 2015). Parawira (2009) confirmed that these types of biomass account for approximately 74 % of total energy usage in sub-Saharan Africa compared to the 25 % in Latin America and 37 % in Asia. There are however disadvantages to using these fuels as the current rate of extracting these fuels is not regarded as sustainable. Moreover, these fuels are not efficient energy carriers, their heat release is hard to control, and the harmful gases released pose health risks (Amigun *et al.* 2012).

1.2.4 North America

It is estimated that there are more than 2 100 biogas systems that are operational in the United States, with the potential for more than 11 000 new systems to be built (USDA 2014, ABC 2016). American Biogas Council (ABC) stated that 171 of these digesters (producing 100 MW) are on agricultural land, 1 500 are located at treatment plants for wastewater (where only 250 digesters use the biogas produced) and 563 are located at landfills (ABC 2016). Furthermore, the biogas production potential of the United States is estimated at 654 billion cubic feet/year. If fully realised, these systems could yield sufficient energy to power about three million American households and decrease methane emissions equal to 40 to 54 million tonnes of greenhouse gas emissions by 2030 (USDA 2014).

1.2.5 South America

Currently, Brazil has 127 biogas plants, which are operating mainly with animal and municipal waste; it is however estimated that about 100 million m^3 methane could be produced every day from waste water, municipal waste, agricultural waste and animal waste in Brazil (Energy-decentral 2017).

By comparison, the total consumption of natural gas in Brazil reached 108 million m^3 per day in 2013. Given this potential, biogas utilisation has not yet taken off and despite the huge potential of generating energy from crop residues/by-products and animal manure/slurry, up to 50 % are currently still considered as mere waste, and as an environmental problem. It was found that this is a result of lack of knowledge and limited access to appropriate technologies (Energy-decentral 2017).

In other South American countries such as the rural areas of tropical regions like Costa Rica and Colombia, and the hilly parts of Peru and Bolivia, biogas plants have been in use since the 1980s (Pérez *et al*. 2014). These countries make use of the same simple constructions such as used in Asia with small-scale domestic digesters containing a volume of 2-10 m^3.

2.0 Sustainability movements

2.1 Global sustainability movement

The world currently faces various challenges in terms of sustainable living. This is supported by the United Nations Development Programme's statement that it is imperative today to foster sustainable development (UNDP 2017). To this end the UNDP developed the Sustainable Development Goals (SDGs), also known as the Global Goals (UNDP 2017). This is a worldwide call to end poverty, safeguard the planet and make sure that all people flourish and live in peace. These 17 SDGs build on the Millennium Development Goals, and include among others current issues such as climatic change, achieving economic equality, and promoting innovation, sustainable utilisation and peace and justice (UN 2015). These goals are interconnected and work in partnership to achieve sustainable living for future generations.

APPENDIX A: FIGURE OF 17 GLOBAL SUSTAINABLE DEVELOPMENT GOALS (UNDP 2017)

APPENDIX A illustrates the 17 Sustainable Development Goals as stated by the UNDP 2017. Biogas utilisation has the potential to address ten of these goals, namely; no poverty (goal 1), zero hunger (goal 2), good health and well-being (goal 3), affordable and clean energy (goal 7), decent work and economic growth (goal 8), industry, innovation and infrastructure (goal 9), sustainable cities and communities (goal 11), responsible consumption and production (goal 12), climate action (goal 13) and life on land (goal 15).

With a current global population of 7.5 billion people (Worldometers.info 2017), it is estimated that one billion people are still living in extreme poverty, with income inequality worldwide continuing to increase (UN 2013). The impact of climate change threatens to accelerate in the absence of sufficient safety measures and it is required to promote the integrated and sustainable management of ecosystems and associated natural resources, especially the global population forecasted to reach about 10 billion in 2056 (Carter and Gulati 2014). This is projected at a current growth rate of 1.11 % (Worldometers.info 2017). The United Nations stated that there is thus a need to take the necessary mitigating steps in an effort to accomplish global sustainability (UN 2013).

2.2 Sustainability in South Africa

In 2008, South Africa adopted the National Framework for Sustainable Development (NFSD) described by the Department of Environmental Affairs (DEA) of which the purpose was to outline the country's vision for sustainable development and to specify strategic interventions that are required to re-orientate South Africa's development path to one that is more sustainable (DEA 2008). According to this report, "*South Africa aspires to be a sustainable, economically prosperous and self-reliant nation that safeguards its democracy by meeting the fundamental human needs of its people, by managing its limited ecological resources responsibly for current and future generations, and by advancing efficient and effective integrated planning and governance through national, regional and global collaboration*" (DEA 2008).

The 2008 report acknowledges the growing impact of economic growth and development on environmental systems and natural resources (DEA 2008). In response, the NFSD commits South Africa in the long-term to a programme of resource decoupling (DEA 2013). Decoupling refers to the ability of an economy to grow without simultaneously escalating environmental pressure. In 2011, the United Nations Environment Programme (UNEP) warned that humanity could annually devour some 140 billion tonnes of biomass, fossil fuels and minerals by 2050, unless nations can start decoupling economic growth from the rate of natural resource consumption (UNEP 2011).

The NSFD also describes principles and trends in terms of sustainability in South Africa, and suggests a set of actions that can be implemented through partnerships with civil society as well as through cooperative governance practices (DEA 2013, DEA 2016).

The National Strategy for Sustainable Development and Action Plan (NSSD) elaborates on the NFSD and other initiatives to address issues of sustainability by non-governmental organisations (NGOs), academia, the business sector, government, civil society and other important role players in South Africa. By recognising the need for new interventions to promote sustainable development, the NSSD makes a valuable contribution towards understanding and achieving sustainable development (DEA 2013, DEA 2016).

South Africa has adopted a systems approach to sustainability which is one where "…*the economic system, the socio-political system and the ecosystem are embedded within each other, and then integrated through the governance system that holds all the other systems together in a legitimate regulatory framework. Sustainability implies the continuous and* *mutually compatible integration of these systems over time. Sustainable development means making sure that these systems remain mutually compatible as the key development challenges are met through specific actions and interventions to eradicate poverty and severe inequalities*" (DEA 2008, DEA 2013, DEA 2016).

2.3 How South Africa compares with the world

To compare South Africa's overall progress towards environmental sustainability with other countries ESI is used. The ESI measures complete progress and provides a complex environmental profile of national environmental stewardship based on a collation of factors resulting from a variety of datasets (SEDAC, 2017, ESI 2017). The ESI tracks 76 features of environmental sustainability, including efforts towards environmental management, contributions made to protect the global commons, natural resource endowments, pollution levels (past and present), and the capacity of a society to perform better on the environmental front (SEDAC 2017).

South Africa ranked 93rd out of 146 countries on the Environmental Sustainability Index in 2005 (DEA 2013). The score of 46.2 positions it below many of its southern African Development Community (SADC) neighbours. Compared to New Partnership for Africa's Development (NEPAD) members, South Africa came 20th out of 40. Gabon, the Central African Republic, Namibia, and Botswana took the first four places (DEA 2013). However, after 2006, the ESI was replaced by the Environmental Performance Index (EPI) that placed an even greater focus on environmental issues for which governments can be held responsible (DEA 2013).

It is a harsh reality that out of the 132 nations that were evaluated, South Africa fared extremely poorly at 128, with a low total score showing a worsening trend (Emerson *et al.* 2012, DEA 2013). The country is also named as the worst performer out of the 21 countries located in sub-Saharan Africa, with Mozambique and Angola ranking at numbers 12 and 13. South Africa's ecosystem vitality (environmental management) ranked as poor and deteriorating, while its environmental health (environmental impacts on human health) is seen as poor but improving (DEA 2013).

This poor environmental performance is ascribed to the ways in which the country's water shortages are managed, its contribution to air pollution and climate change, poor public health, as well as unstustainable mining and agricultural practices (OECD 2013). This reaffirms the conclusions of the 2005 Environmental Sustainability Index that focused on South Africa's air and water quality, highlighting the country's role in advancing climate change and human vulnerability as particular problems (DEA 2008, DEA 2013, OECD 2013).

The DEA states that, in response, it is critical that government implements applicable strategies and structures to overturn the situation in partnership with academia, community organisations and business in order to take the steps that are required to reverse the numerous identified negative trends (DEA 2013).

In 2014, South Africa showed improvement in its EPI done by Yale University where the country moved up to an overall rank of 72 out of 178 countries (EPI 2014).

2.4 Biogas generation as a sustainable strategy to improve South Africa's environmental performance

Biogas does what few other renewable energy technologies do, which is to integrate waste and energy technology (Biogas 2013). With the acknowledgement of the critical importance of moving towards more sustainable development in South Africa (DEA 2013, DEA 2016), the use of biogas digesters for electricity generation and efficient waste management could play a defining role to improve and contribute to all three pillars of sustainability – i.e. improving social dynamics (job creation, public health and living standards), promoting the new business opportunities and protecting natural resources and environmental systems. The National Framework for Sustainable Development (NFSD) indicates that such strategic interventions are needed to re-direct South Africa's development towards a more sustainable path (UN 1987, DEA 2008, DEA 2013).

The Department of Energy (DoE) is assigned with the task to ensure secure and sustainable energy delivery needed for South Africa's socio-economic development. The DoE's National Development Plan (NDP) stipulates that South Africa will have an energy sector that promotes economic growth and development through sufficient investment in energy infrastructure by 2030 (DoE 2016). It further foresees that at least 95 per cent of the South African populace will have access to either grid or off-grid electricity (DoE 2016).

Energy policies implemented should also address sustainability by mitigating the effects of climate change (DEA 2017) providing extra motivation for the Department of Energy to include technologies such as gas, biomass, solar, thermal and wind resources to meet the South Africa's future electricity needs (DoE 2016, DEA 2017). The plan proposes the use of renewable resources such as gas as feasible alternatives to coal, and suggests that by 2030 these alternatives will supply at least 20 000 MW of the additional 29 000 MW of electricity needed (DoE 2015, DoE, 2016).

Decisions regarding the energy mix of South Africa's electricity supply industry should also take into account its potential environmental impact, and the South African government has made several commitments relating to minimising the environmental impact thereof. These include, for example, a 34 % reduction in greenhouse gas emissions by 2020 (Teljeur *et al.* 2016).

2.4.1 Access to affordable and clean energy in South Africa

One of the most significant human-derived obstacles to overcome in terms of sustainability is the access and supply to affordable and clean energy – SDG goal 7 (SAGEN and SABIA 2016, UNDP 2017). The United Nations (UN 2013) predicts that the energy needs of hundreds of millions of households worldwide are likely to remain unmet unless substantial headway is made in guaranteeing access to modern energy sources. The World Wide Fund for Nature's (WWF) Food Energy Water (FEW) report specifies energy as a major force in ensuring effectiveness and sustainability in the farming sector (Carter and Gulati 2014). With the ever-present electricity crisis and the recurrent consequences thereof, unsustainable production and associated consumption have brought about huge economic and social costs to South Africa making the need for improvement and innovations in this sector critical (Teljeur *et al.* 2016).

Teljeur *et al.* (2016) found that as electricity prices rose and the reserve margin dropped in the 2000s, attention shifted to large-scale renewable energy projects that could increase supply relatively quickly. In 2009, NERSA developed renewable energy feed-in tariffs, replaced in 2011 by the Department of Energy (DoE) with a competitive bidding process for renewable energy, the Renewable Energy Independent Power Project Procurement Programme (REIPPPP), consisting of mostly solar and wind power generation technology (DoE 2015, DoE 2016, GreenCape 2017c). Independent Power Producers (IPPs) were then introduced into the electricity supply industry through the highly successful REIPPPP which, towards the end of 2015, had attracted R192 billion in private investments in 92 projects, contributing 6 327 MW of contracted capacity. The Department of Energy's IPP unit is currently expanding the competitive procurement programme to include cogeneration, coal and gas-to-power generation projects (DoE 2016, Teljeur *et al.* 2016).

Since 2007 and until August 2015, South Africa was faced with an unprecedented supply crunch in the electricity sector with Eskom (state-owned vertically-integrated electricity company) being unable to meet peak electricity demands, leading to recurrent load shedding/electricity power cuts (Teljeur *et al.* 2016). This situation was triggered by a number of causes, including delays in the construction and commissioning of coal-fired power stations (Medupi and Kusile); Eskom's strained financial position; unplanned outages, and poor maintenance of ageing electricity plants. The critical challenge for the power sector is thus to restore security of electricity supply and ensure sufficient electricity is generated to meet demand (Teljeur *et al.* 2016).

South Africa has a very specific electricity load profile. Peak energy demand hours are in the early morning between 07h00 and 10h00 and in the evening between 18h00 and 20h00. This is largely because the majority of South African households utilise electricity for cooking and heating as opposed to gas which is used in many European countries and the United States (Griffiths 2013). This means that our peak demand requirement does not match the period in which peak solar radiation gives the highest generation for solar energy. Wind energy profiles also do not fit in predictably with this demand profile. With that said, it is clear that a potential gap for biogas electricity generation could develop to alleviate electricity demand in peak hours. As long as a biogas plant is maintained and correctly supplied with feedstock, generation of biogas remains a very suitable option for the generation of additional power to alleviate peak power energy demand (Griffiths, 2013).

The biogas produced can be applied as electricity through the use of gas turbines or used as gas. The electricity generated could potentially be fed into the national electricity grid if sufficient and effective policies and legislations are in place to do so. Available incentives and rebates make farm-scale biogas plants a very attractive option for farms looking to reduce their carbon footprint and save on electricity bills (Griffiths 2013, Scharfy *et al.* 2017). Government-subsidised rural biogas generation as is taking place in China and India is however not implemented on a wide scale in South Africa as yet (SAGEN and SABIA 2016).

In addition, GreenCape states that as a liquefied petroleum gas (LPG) replacement, biogas provides sufficient heating and electricity generation with a current market value of more than R450 million, and a potential market of R18 billion (GreenCape 2017b).

2.4.2 Waste management in South Africa

In many Asian countries, waste is regarded a valued resource of renewable energy (Greben and Oelofse 2009). The DEA have stated in their Environmental Outlook Report 2013 that South Africa's economic development, rate of urbanisation and population growth, have led to the increased generation of waste requiring the implementation of effective programmes and policies for waste management (DEA 2013, DEA 2016).

This makes the uninhibited generation of waste an unfortunate reality in South Africa, and presents waste management as another significant human-derived obstacle to overcome in terms of sustainability, potentially addressing goal 11 and 12 of the SDGs: sustainable cities and communities (goal 11), and responsible consumption and production (goal 12) (UNDP 2017, SAGEN and SABIA 2016). The management of waste in a developing country such as South Africa plays a key role in its sustainability status and the progress of a country (Msibi 2015), therefore the use of biogas digesters supports the development of South Africa's sustainability movement as it contributes to efficient waste management (Biogas 2013). With the increasing costs of fossil fuel and electricity, there is a growing interest for biogas as a source of affordable and renewable energy, as well as an effective waste management method (Biogas 2013, GreenCape 2017c). In 2009, it was estimated that in South Africa, some 40 per cent of waste generated consists of organic material that supplies biogas when digested (Greben and Oelofse 2009).

Biogas can be used to supply energy in the form of heat, combined heat and power (CHP) or fuel for vehicles or machinery. One of the significant benefits of using a biogas plant as a renewable energy solution is its capacity to be situated at any location where waste feedstock is available (SAGEN and SABIA, 2016). This makes it particularly suitable for rural areas and agricultural areas.

The success of biogas digesters rely largely on the sufficient use of waste as feedstocks for specific digesters (Biogas 2013). The WWF FEW report (Carter and Gulati 2014) states that nine million tonnes of food is wasted every year (34 % of all food) and that energy lost through this wastage has the potential to power Johannesburg for 20 years. It also stated that agriculture production is the major sector where mostly organic waste is generated in South Africa which, and if managed correctly, could be highly potential feedstocks for biogas digester systems (GreenCape 2017b). Industry and mining can also supply feedstock (DEA 2009b) through wastewater or discharge, the biological treatment and discarding of solid waste, and the burning of waste (NT 2013). Households, institutions and commercial businesses could also contribute to waste streams.

A study done by Potgieter (2011) maintains that the potential of biomass as renewable energy resource is the total energy value of all the different available types of biomass that can realistically be transformed into bioenergy. The study found that the potential of biomass as renewable energy resource is more than the annual consumption of primary energy in the world.

A DEA report on national waste quantification and waste information systems, also lists issues which show a continuation of challenges for effective waste management. These challenges highlighted several shortcomings such as flawed data collection; a lack of compliance and enforcement capacity; a lack of incentives to reduce, recycle or reuse waste; a lack of stakeholder education and awareness; a lack of local government support for waste reduction; high waste management costs, and a shortage of suitable land available for waste disposal (DEA 2009a).

Waste management in South Africa still largely relies on landfills which are the cheapest waste disposal option due to low costs and availability of land. Methane emissions from landfill sites in urban areas contribute about two per cent to the total GHG (greenhouse gas) emissions in South Africa. However, these estimates for landfill methane emissions remain uncertain as data on landfill depths, actual levels of waste disposed of, and the composition of waste, remains lacking (NT 2013).

While municipal waste is not the largest waste volume in South Africa, it is the most significant in terms of funding and the impact that it has on the day-to-day lives of ordinary people (DEA 2009b). Municipal waste consists mostly of mainline recyclables, organics (greens and garden waste), building rubble and non-recyclables (DEA 2013).

The National Environmental Management: Waste Act (No. 59 of 2008) (NEM:WA) and the National Waste Management Strategy (NWMS) (2011) obliges municipalities to apply alternative waste management actions in order to redirect waste from landfills (GreenCape 2017b). It is likely that 65 per cent of waste (totalling about 38 million tonnes) can be recycled and put to alternative uses rather than being sent to landfills (DEA 2013). If based on global trends, sending waste away from landfills could increase revenue from this sector: in 2014, the Department of Science and Technology (DST) projected that an extra R17 billion/year worth of resources could be made accessible if 100 % of the identified waste streams could be recycled (GreenCape 2017b).

It is predicted that by 2019, South Africa is aiming to reach the target of 20 % waste division (DEA&DP 2015). For the Western Cape this means diverting 1.5 million tonnes per annum, of which 800 000 tonnes are municipal solid waste (DEDAT 2016). This will not be easily done, as the implementation of alternative waste management is relatively expensive due to the initial capital costs that usually stem from the need for new infrastructure, and will be a financial constraint based on current budget and location (GreenCape 2017b).

National legislation changes and the potential provincial goal to ban the landfill of organics by 2026 are supporting the growth of organic waste beneficiation (GreenCape 2017b, GreenCape 2017c). This will result in the remaining waste largely being dry recyclable waste with less risk of contamination and also making more organic waste available for possible anaerobic digestion process (GreenCape 2017b). Inhibiting factors of this process currently are policies and legislations prohibiting the reuse of food waste in South Africa (Von Bormann and Gulati 2014).

3.0 Anaerobic digestion as a sustainable strategy to meet energy demands and waste management challenges

Anaerobic digestion (AD) is simple biological process which produces biogas via the natural anaerobic bacterial decomposition of organic material including plant material, animals and their wastes and waste water (Dennis and Burke 2001, Arbon 2005, Shah *et al.* 2014, Biogas 2013, GreenCape 2014, GreenCape 2017c). AD uses the same biological processes, but under the controlled conditions of a digester system, that happen at landfill sites (Arbon 2005).

The four-stage process (Figure 2) of hydrolysis, acidogenesis, acetogenesis and methanogenesis, occurs in a warmed and sealed biogas digester tank where bacteria ferment organic matter in oxygen-free conditions to produce biogas and digestate. The organic material used is often referred to as feedstock. Biogas digesters can operate on small, medium or large scale (APPENDIX B). Figure 2 illustrates biogas digesters system used for raw fertiliser production, electrical energy generation and heat energy generation. (Source: Dussadee *et al*. 2016).

AD has been used for more than a century to stabilise municipal sewage and many other types of industrial waste (Dennis and Burke 2001). Mostly wastewater treatment at municipality plants uses AD to transform solid waste to gas. The anaerobic process significantly reduces the pathogens present in the slurry and removes many of the odorous compounds (Dennis and Burke 2001).

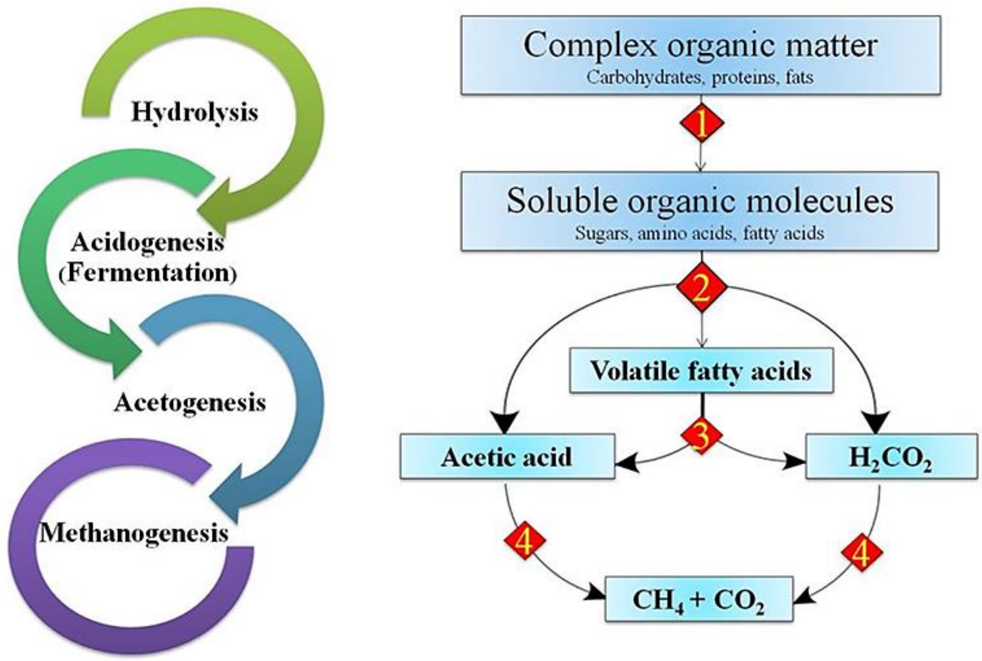

Figure 2: Illustration of the four stages of the anaerobic digestion process
(Source: Dussadee *et al*. 2016).

Biogas produced is a naturally occurring blend of methane CH_4 (50–75 %), carbon dioxide CO_2 (25–45 %), hydrogen sulphide H_2S (0-3 %), hydrogen H_2 (0-1 %), carbon monoxide CO (0–2 %), nitrogen N_2 (0–2 %), ammonia NH_3 (0-1%), oxygen O_2 (0–2 %), and water H_2O (2–7 %) (Shah *et al.* 2014). Biogas is a colourless and odourless gas that burns with a clear blue flame and is in that sense similar to LPG gas (Ghimire 2013, Nyns *et al.* 2014). However, these values may vary as the percentage amount per compound varies for different feedstocks used.

Once generated and stored, biogas presents a flexible alternative for non-renewable energy sources and has mainly been used around the world for household cooking and heating, as well as for gas lamps and absorption refrigeration systems. Biogas also has many other significant domestic and industrial uses. This is particularly true for rural areas, where the use of biogas can replace the burning of wood for fuel for cooking and heating leading to increased health and environmental benefits (Biogas 2013, Msibi 2015). Its use to power electric generators is also well established especially in some European countries and in North America (Dennis and Burke 2001).

It is estimated that one cubic metre (1 m^3) of pure bio-methane contains approximately 10 kWh of chemical energy (Dillon 2011). Biogas contains approximately 60 % bio-methane and therefore 1 m^3 of biogas comprises about 6 kWh of chemical energy (Biogas 2013). A co-generation engine is used to convert this to electrical energy, to produce both heat and electricity. Other studies have also found that by analysing the production of thermal energy in gas boilers and the production of both thermal and electrical energy in related units, 1 m^3 of biogas in associated production of energy, 2.1 kWh of electrical energy and 2.9 kWh of heat are obtained (Arbon 2005).

The average efficacy of methanogenesis alone produces approximately 0.24 m^3 of methane from 1 kg of dry organic matter. One cubic metre of biogas with the calorific value (relating to the amount of energy contained) of 26 MJ /m^3 may replace 0.77 m^3 of natural gas with 33.5 MJ calorific value, 1.1 kg of hard coal with 23.4 MJ calorific value, or 2 kg of firewood of 13.3 MJ calorific value (Arbon 2005). These values may only give a broad idea as the biogas-to-energy technology has improved since 2005, when the data above was determined. These energy values are based on averages and ultimately prove the potential of biogas. However, these energy values may differ as they are dependent on feedstock quality and type, as well as type of digester mechanisms used.

Additionally, its production creates digestate (high-quality nutrient-rich soil conditioner) and enables the production of petrochemical substitutes. This makes biogas a suitable replacement of fossil resources on many levels (Dennis and Burke 2001, Culhane 2017). Digestate has physical and chemical characteristics that are comparable to manure compost and is the by-product of heat and methane production in a biogas plant (Torquati *et al.* 2014). Digestate, whether in a liquid or solid form, has a high mineral nitrogen (N_2) content and other macro- and microelements that are needed for plant growth and has potential to be converted to a fertiliser in South Africa (Dillon 2011). See Figure 3 (Source: Dillon 2011).

The most important environmental benefit of agricultural biogas however probably lies in the contribution it can make to reduce (CH_4) emissions arising from the natural decay of organic matter, and in the overall decrease in carbon dioxide (CO_2) emissions that can be brought about by the use of alternative energy sources instead of conventional fossil fuels (Torquati *et al.* 2014).

However, according to Torquati *et al.* (2014) these benefits are not easily measured. Obtaining renewable energy is a particularly complex process, as it involves different types of biomass as well as a variety of chemical, physical and thermal processes used by different digestion technologies. Biomass feedstock can vary from municipal wet (organic) waste and food waste to agricultural crops and harvesting residues including manure. Similarly complex are the decisions that have to be made about the best ways to use the digestate and biogas produced. This complexity thus presents many challenges to analysing the energy and environmental benefits of biogas production (Torquati *et al.* 2014).

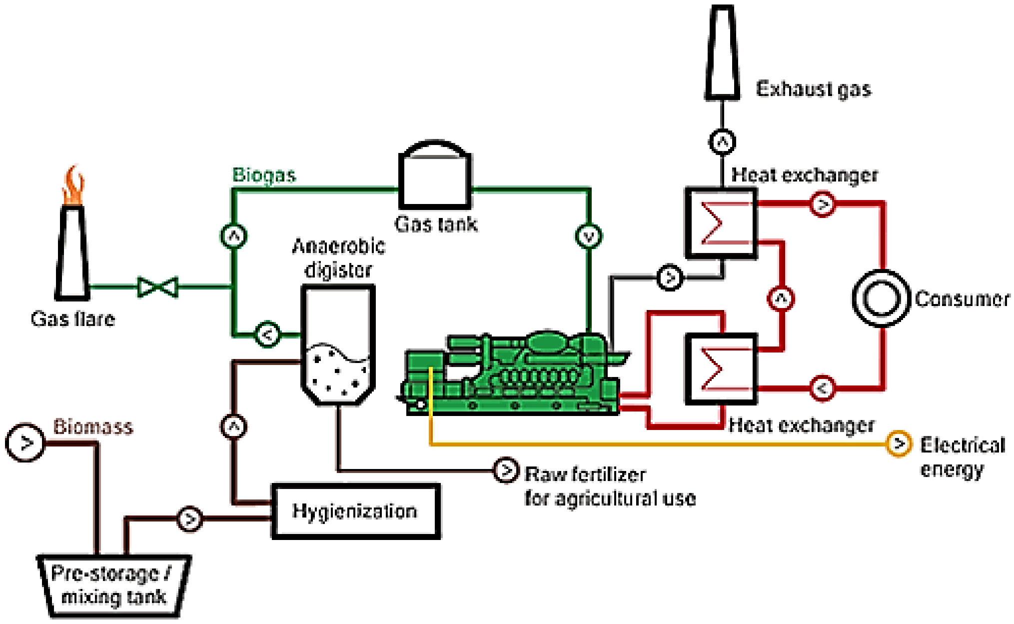

Figure 3: Illustration of anaerobic digester and biogas generating system used for raw fertiliser production, electrical energy generation and heat energy generation. (Source: Dillon 2011)

3.1 Feedstock importance and availability

When compared to wind and solar as renewable energy technologies, biogas digesters do not require a primary resource such as wind or sun, but requires a secondary resource referred to as feedstock (SAGEN and SABIA 2016). Feedstocks are essential to ensure successful anaerobic digestion in biogas digesters (GreenCape 2017c). For a particular biogas digester to run productively, it is vital that feedstocks are correctly used and managed. Depending on their organic content different feedstocks generate different amounts of methane. The methane content of the biogas reveals its energy value. If the feedstock quality is low, the biogas produced will have lower methane content, resulting in lower energy value (NNFCC 2016). Maize and grass fodder, for example, produce more methane per m^3 of biogas than livestock manure, while livestock manure has greater potential than human sewage waste (Dussadee *et al*. 2016).

It was stated by The National Non-Food Crops Centre (NNFCC) that in order for biogas plants to be viable over its 10 to 20-year lifespan, consistent quality of feedstock is needed (NNFCC 2016). What is more, as a digester needs to be fed constantly and consistently to run productively for 24 hours per day, requiring that feedstocks must be accessible at all times. The removal of digested sludge also involves regular management as digestate accounts for up to 95 % of the feedstock, and could lead to a digester malfunctioning if it is not removed on a regular basis (NNFCC 2016).

If organic feedstock is allowed to naturally decompose it will lead to a decrease in the methane production (NNFCC 2016). The feedstock should thus be fresh, but also of certain water content. Feedstocks left outside for long periods of time could be rendered less effective because of moisture loss. It is vital for the success of any biogas digester plant that these plants are fitted out with adequate feedstock storage facilities to ensure consistency and quality of stocks (NNFCC 2016).

While all organic material could potentially be used to produce biogas, not all possibilities of organic matter production are relevant to the South African industry. The few existing large-scale biogas digester systems currently operational in South Africa are mostly used as a problem-solving mechanism and mainly relay solid and hazardous waste from landfills. In contrast, international government incentive programmes have enabled many more feedstock avenues to be thoroughly utilised at larger scale biogas digester systems in other places in the world (SAGEN and SABIA 2016).

This approach is not necessarily relevant to South Africa, as water scarcity and the reliance of a significant number of people on subsistence farming impacts the availability of feedstocks. For example, growing carbohydrate-rich maize as a feedstock for biogas digesters is not necessarily viable in South Africa, and is more appropriate to developed countries such as the United States of America or Germany (SAGEN and SABIA 2016). It is thus essential when considering South Africa's biogas digester industry, or when constructing an ideal conceptual model, that realistic and available feedstock avenues should be explored.

3.2 Feedstock types in South Africa

The following feedstock types, agricultural crop waste, manure (poultry, cattle and dairy farms/feedlots), abattoir waste, municipal solid waste and sewage are seen as the feedstocks with the highest potential for a country such as South Africa (Smith 2011, Msibi 2015, SAGEN and SABIA 2016).

3.2.1 Agricultural crop waste

In South Africa a number of agricultural outputs exist, and agricultural waste in this study specifically refers to crop and plantation wastes such as vegetables, sugar cane and fruit, and exclude manure and abattoir waste. These outputs are typically seen as waste streams that could be redirected as resources for other farms and are thus not likely to be redirected towards anaerobic digestion. Examples are fruit pulp used for livestock feed, and compost used for fertiliser (SAGEN and SABIA 2016). The potential for the implementation of anaerobic digestion in South Africa therefore only becomes a possibility when agricultural waste becomes available for bio-digestion and is not redirected for alternative uses and/or other purposes. It is against this background that SAGEN and SABIA (2016) believes that anaerobic digestion has the highest potential to be implemented on farms that could benefit from reduced electricity and/or heat costs, and costs incurred with waste treatment, storage and transportation.

Van der Merwe (2014) maintained that crop remains are often classified as so-called production residues, and are produced as an important part of the commercial production of agricultural crops, but not as the end product. This can include bruised, undersized or misshapen fruit and vegetables separated on the farm or in a pack-house that are regarded as unsuitable for sale; or vegetable and fruit toppings, roots and leaves that are removed as before sale (Van der Merwe 2014).

Van der Merwe (2014) further states that while there are some agricultural products that are not necessarily effective for AD, it is often found that its by-products are suitable for AD. An example is sugarcane, where the by-products from sugar-milling such as wastewater and filter cake are rich in organics and may be regarded a valuable feedstock for biogas generation (Magama *et al.* 2015). Sugarcane itself is not a viable feedstock as it consists mostly of water with 15 % fibre and 15 % sugar; once the sugar water has been removed from the cane, the remaining fibre is burnt to yield steam and electricity for on-site use (Van der Merwe 2014) and therefore an AD technology is not required.

With South Africa having a large wine industry, some studies have considered grape pomace as a potential feedstock for the production of biogas, especially in the Western Cape where most of the wine industry is based. However, a study found that the viability of using a biogas digester is determined by the finances of the facility and the availability of organic feedstock throughout the year (Dillon 2011). The study established that as the wine and grape industry is dependent on seasonal production, generation of electricity from grape pomace for a single farm alone is not sustainable. One metric tonne of grape pomace will yield about 230 m^3 of biogas; one tonne of grape pomace should produce approximately 828 kWh of renewable electricity. The study concludes that joint ventures within the wine industry could result in communal digesters servicing surrounding wineries, making it more viable as a sustainable solution to winery waste (Dillon 2011).

3.2.2 Manure (poultry, cattle and dairy farms/feedlots)

Manure and abattoir wastes are both so relevant in the South African biogas industry that they deserve separate explanations and are for this study not included under a combined heading of agricultural wastes. DAFF (2015) estimated that in 2002 South Africa approximately had 14 million cattle: 1.6 million commercial dairy farms, 6.6 million beef or dual purpose cattle and 5.7 million communal cattle. As an agricultural by-product from dairy farms, feedlots and other livestock farms (such as chicken farms), manure waste is often used as an untreated fertiliser or stored in waste lagoons creating enormous potential for biogas generation (Dennis and Burke 2001). The use of manure for on-site anaerobic digestion could considerably improve the handling process and contribute to the elimination of potential negative environmental impacts, such as the spread of unwanted pathogens and the accumulation of harmful nitrates in the water table (SAGEN and SABIA 2016). In return, the electricity and heat produced on site could help to bring down running costs and reduce the farm's dependence on the grid (Baltic Deal 2012). The digested sludge as by-product could be used as a treated soil conditioner on the specific farm or supplied to commercial and domestic agricultural fertiliser producers.

A study by Msibi (2015) stated that availability of feedstocks for domestic low-income households in South Africa is one of the key factors when considering domestic scale biogas digesters. When referring to low-income-domestic/rural/small scale application of manure, Msibi (2015) established that where enough cattle and pig manure are available, a substantial number of households could benefit from community digesters but that it will be more feasible for community digesters to be fed a mixture of sewage and waste such as pig and cattle dung. However, Msibi (2015) maintained that due to the small average number of chickens kept by a low-income South African household, chicken manure alone is not enough to operate a biogas digester on a small domestic scale.

On the other hand, the South African Poultry Association (SAPA) stated that the South African poultry industry totalled at 142 million birds in 2014 (SAPA 2014). Chicken manure has a high production potential of 80 L biogas/kg when compared to cow manures and faeces producing 40 L of biogas/kg (Dillon 2011, Belostotskiy *et al.* 2013). With this said it is clear that the poultry industry as a potential feedstock supplier for AD processes holds promise for community-based and medium to larger scale biogas digester industries in South Africa, and should not be overlooked.

3.2.3 Abattoir waste

The generation of power in South Africa is not cheap, and recent studies have shown that electricity is one of the biggest expenses at an abattoir (Swanepoel 2014). The limits placed in South Africa on the disposal of hazardous abattoir waste, together with the benefit of generating heat and electricity that are tailored to the abattoir's operational requirements, creates an excellent opportunity for abattoirs to implement anaerobic digester implementation (SAGEN and SABIA 2016). Due to the large amounts of organics that abattoir wastewater contains NEM:WA (2008) restricts this wastewater from entering conventional wastewater treatment plants. Similarly Neethling (2014) stated that burning and sterilising waste has been limited because of threatening negative environmental impacts and the risks of pathogens spreading. Treating, storing and transporting wastes to landfills that accept such hazardous materials could potentially increase the costs of running an abattoir. Swanepoel (2014) found that intestines (gut contents) and manure proved to be the abattoir waste with the highest potential and efficiency for biogas generation. Swanepoel (2014) further maintains that South African abattoirs slaughter at a rate of 150 units per day, generating about 12 T of by-products. A biogas plant with that amount used as feedstock may generate about 115 kWh of electricity/day (Van Rooyen 2013). A study by Uduak *et al.* (2012) further confirmed that implementing a biogas plant using abattoir wastes as fuel could prove to be cost-efficient. GreenCape (2017c) also stated that medium scale (>50kWe; <1MW) biogas facilities at abattoirs showed to be financially viable at the middle to high end of the size range, when there are high waste management costs and full utilisation of energy on-site.

3.2.4 Municipal solid waste

Organic food waste is divided at source to separate domestic, industrial and commercial waste streams, and can be used for on-site composting or directed to landfills. Organic food waste used as feedstock for an anaerobic digester has the potential to generate electricity and/or heat, while the digested sludge could be applied as fertiliser.

Similar to abattoirs, commercial beverage and food production set-ups such as cheese factories, breweries and fruit and vegetable processing facilities could use their organic wastes to produce their own heat and electricity on site (Swanepoel 2014, SAGEN and SABIA 2016). Recent studies have stated that less strict waste laws for these waste streams (as opposed to abattoir waste), result in most of these waste streams being sent to landfills (SAGEN and SABIA 2016). The study also found that the implementation of anaerobic digestion at operations such as these could reduce transport costs to landfills and costs incurred for heat and electricity generation. On a larger scale, it would significantly reduce the amount of waste redirected to landfills (SAGEN and SABIA 2016).

3.2.5 *Sewage*

Biogas produced at waste water treatment works (WWTW) could be used to provide electricity for the up- and downstream treatment processes. Waste water is a well-known feedstock in the biogas industry around the world as sewage sludge has a high methane volume in relation to biogas produced from other feedstocks (Bachman 2015). The main feedstock for anaerobic digestion (AD) in WWTW is sewage sludge. Biogas production at a WWTW starts with sewage sludge pre-treatment, followed by AD and biogas production, and ends with post-treatment of the digested sludge and the gas produced (Bachman 2015). Like all other biogas by-products, the sludge has no smell and is nitrate-rich making it suitable to be used as agricultural fertiliser (SAGEN and SABIA 2016).

Conventional wastewater treatments use AD to reduce the pathogen load and water content of the sludge and to remove odours (GIZ & SALGA 2015). WWTWs that do not have the conventional digestion processes in place would need a greater capital input to establish a biogas unit, and for this reason it will be necessary to evaluate the viability of such a WWTW against its estimated economic benefits (GIZ & SALGA 2015a).

Rural housing developments, schools and clinics that are not connected to a wastewater system could produce electricity or gas as fuel for cooking and heating purposes by using AD to treat their sewage wastes. In addition, using AD could have the benefit of preventing potentially dangerous pathogens from entering the groundwater (Msibi 2015, SAGEN and SABIA 2016). One of the reasons why human excreta has not taken off as possible feedstock is that the World Health Organisation has stated that pathogen reduction by mesophilic AD is insufficient to allow subsequent use of human excreta as potential fertiliser derived from biogas digesters (Bond and Templeton 2011).

3.3 Potential use of digestate as fertiliser

Digestate, also sometimes referred to as biogas slurry, is the by-product of methane and heat production in a biogas plant using organic waste (Surendra *et al.* 2014). Depending on the biogas technology used, digestate could be in either a solid or a liquid form. Digestate comprises many macro- and microelements required for plant growth such as nitrates, ammonia and phosphates. Mineral nitrogen (N_2) is available in the form of ammonium. The availability of nitrogen (N) for agricultural crops is the most common factor that limits growth (Makádi *et al.* 2012). This makes digestate a beneficial source of nutrients and an effective fertiliser for crops. In addition, the organic elements of digestate can influence the biological, chemical and physical characteristics of soil (Makádi *et al.* 2012).

The solids and liquids of the digestate are mechanically separated, so that the solid part can mix with the lignocellulosic substrate in the compost tank. The liquid part, when biologically stabilised, can be used as fertiliser either with drip fertigation or by direct application into the ground. In the composting system, the digestate is constantly stirred and aerated for three to four months in an effort to lessen the moisture content and to form a stable ready-to-use fertiliser mix (Torquati *et al.* 2014). Digestate can also infiltrate the soil faster than normal fertiliser reducing the risk of nitrogen losses (Surendra *et al.* 2014).

The quality of digestate as a fertiliser is determined by the input materials and the retention time (Makádi *et al.* 2012). A longer retention time results in a lower organic content, because of more effective methanogenesis (Szűcs *et al.* 2006). According to Burton *et al.* (2009) the typical composition of digestate is predominantly cellulose, lignin, biomass sludge and inorganic components. In the absence of pathogens or potentially toxic elements, the digestate makes an ideal bio fertiliser, often after a period of aerobic treatment to degrade lignin and oxidise ammonia to nitrate (Burton *et al.* 2009).

The benefit of digestate use is its ability to make nutrients available within the crop rotation from autumn to spring, when crop nutrient demand grows (Möller *et al.* 2008). The higher nitrogen content of digestate in comparison to compost is the result of the nitrogen concentration effect due to carbon degradation to CO_2, CH_4 and N_2 preservation during AD (Tambone *et al.* 2009). Digestate also contains more phosphorus (P) and potassium (K), assumed to be more readily available than that of composts (Börjesson and Berglund 2007, Tambone *et al.* 2009) making it more suited as a supplement in soils missing these macronutrients. The typical ratio of phosphorus to potassium in digestate is about 1:3 which is very good for rape and grain.

Table 4 illustrates a summary of the nutrient contents of the digestate compared to other organic manure and vermicompost. Vermicomposting is another form of sustainable composting making use of a natural ecological decomposition process. Vermicomposting makes use of various worm species to create a varied mix of decaying vegetable or food waste, bedding materials and vermicast (Surendra *et al.* 2014).

Table 4: Nutrient content of important organic manure (Source: Surendra *et al.* 2014)

Organic manure	**Organic matter (%)**	**C:N**	**N_2(%)**	**P_2O_5 (%)**	**K_2O(%)**
Farm yard manure	25-55	15-20	0.40-0.80	0.60-0.82	0.50-0.65
Biogas slurry	60-73	17-23	1.50-2.25	0.90-1.20	0.80-1.20
Vermicompost	9.80-13.40	-	0.51-1.61	0.19-1.02	0.15-0.73

3.3.1 Effects and application of digestate

Depending on soil types, digestate has a very complex effect on the chemical, physical and biological properties of soils (Makádi *et al.* 2008). It can be applied as a fertiliser to enhance soil quality (Schleiss and Barth 2008) as digestate is suitable to sustain nutrient levels in soils and soil fertility (Tambone *et al.* 2007).

Odlare *et al.* (2008) and Fuchs and Schleiss (2008) report that they have not found noteworthy changes in soil pH where digestate had been applied even though an increase of the soil pH is assumed because of the alkaline nature of digestates. However, the pH of digestate may fluctuate as digestate could comprise several acidic compounds (e.g. Gallic acid), making the regular monitoring of soil pH necessary in cases of long-term use (Makádi *et al.* 2012).

In comparison to the varied organic wastes that are available like sewage sludge, biogas residue, compost and manures with and without mineral nitrogen, biogas digestate was found to be more efficient for promoting microbiological activity in soils (Makádi *et al.* 2012). Substrate induced respiration (SIR) increased with the high amount of easy-degradable carbon that resulted from higher plant growth (Makádi *et al.* 2012).

The application rate of liquid or solid digestate depends on the nitrogen demands of the plant and should be often used when plant nitrogen needs are high (Stinner *et al.* 2008). Because of this high available nutrient content, the use of digestate brought about meaningfully higher above-ground biomass yields in the case of winter and spring wheat compared to farmyard manure and undigested slurry treatment (Stinner *et al.* 2008). Makádi *et al.* (2012) also found liquid digestate treatment led to significantly higher yields of sweet corn and silage maize. Digestate treatment also seems to effectively increase the protein content of plants (Makádi *et al.* 2012).

The efficiency of a digestate is dependent on the composition of co-digested material, the plant species treated and the methods of treatment; co-digestion of different organic materials produces a more effective digestate (Möller *et al.* 2008). While crop yield is a very important economical consideration in plant production, it is offset by the increasing demand for higher quality foods. Digestate application in solid or liquid form could significantly improve the quality of foods without negatively impacting on the environment, which is very significant for promoting a sustainable environment and healthy life (Makádi *et al.* 2012).

3.3.2 Digestate regulation processes in other countries

Sustainable recycling of organic wastes requires clear regulations concerning wastes to be recycled and the methods used, and these regulations differ from country to country (Makádi *et al.* 2012).

In Hungary, the digestate is seen as non-hazardous if it does not comprise sewage or sewage sludge, while if these materials are present the, digestate utilisation will depend on the quality of the supplied material (Makádi *et al.* 2012). In Switzerland the digestate which fits the limits is used as soil conditioner and fertiliser in so-called bio-agriculture (Makádi *et al.* 2012). The BSI PAS110:2010 (British Standards Institution Publically Available Specification) digestate quality assurance scheme is applied in Scotland (SEPA 2017), and if a digestate fulfils the quality requirements, usage criteria and certification system, the Scottish Environment Protection Agency (SEPA) does not apply waste regulatory control. In Germany the origin of the input materials controls the quality of the digestate, and digestates have to satisfy the minimum quality requirements for liquid and solid types determining the minimum nutrients and the maximum pollutants (such as physical contaminants, toxic elements and pathogen organisms) that may be present in the digestate (Siebert *et al.* 2008).

3.3.3 Potential in South African fertiliser industry

South Africa is a net importer of fertilisers, importing all our potassium, as well as 60 % to 70 % of our nitrogen (N) requirements. The South African fertiliser industry is thus fully exposed to world market forces while it functions in a deregulated business environment with no import tariffs or government support. In this deregulated market, fertiliser prices are affected by global prices, currency exchange rates (ZAR/USD) and transport costs (DAFF 2015). This subjects local prices to the same supply and demand drivers as in the international industry. Most of the international fertiliser prices (USD/ton) increase annually and due to the significant depreciation of the local currency, international fertiliser prices increased even more (DAFF 2015).

While the properties of digestate makes it possible to use as fertiliser and renders it suitable for soil improving (Makádi *et al.* 2012), the use of digestate as potential fertiliser has economic and environmental benefits because it could lead to a situation where much less artificial fertilisers could be required for plant production. A study by Gautam *et al.* (2009) found an annual savings of 4 329 T N, 2 109 T of phosphorus and 4 329 kg potassium due to the implementation of biogas digesters in Nepal to replace previously imported chemical fertilisers with the organic form of digestate fertilisers translating into an annual saving of approximately USD 300 000.

South Africa's consumption of fertiliser experienced an increase from 2004 and a decline in 2005 and 2010 to approximately 350000 and 400 000 T respectively (DAFF 2016). The Makádi *et al.* (2012) study found that digestate has a high amount of N_2 particularly in the form of ammonium which is available for plants, making it a suitable substitute for other N fertilisers used in South African applications.

The alkaline pH of digestate could also make soils less acidic, which is seen as serious problem around the world but especially in South Africa. Using digestate instead of artificial fertilisers could further increase the productiveness of over-used and previously poorly managed soil, ultimately contributing towards more sustainable agricultural practices in South Africa (Makádi *et al.* 2012). The study by Makádi *et al.* (2012) concluded that the use of liquid or solid digestate could significantly improve the quantity and quality of foods through even nutrient supply, contribution to healthier lifestyles and well-being.

Figure 4 below illustrates the fertiliser composition in South Africa, showing that nitrogen fertilisers seem to be the most-used fertilisers, followed by potassium and phosphorus.

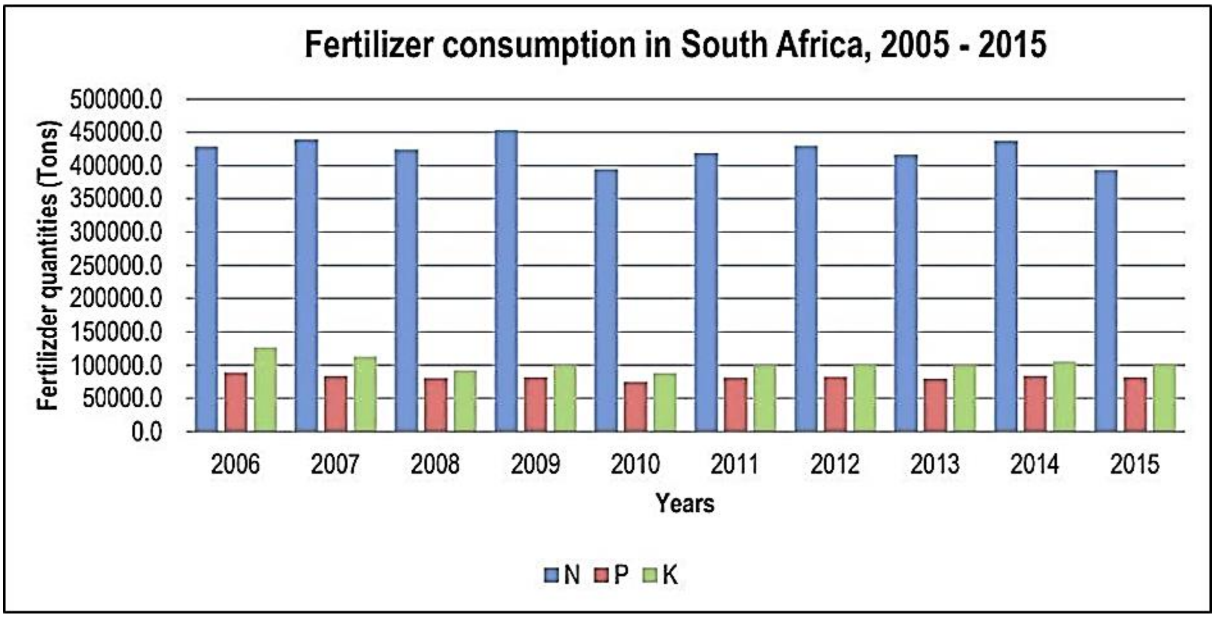

Figure 4: Illustration of the fertiliser consumption in South Africa between 2005 and 2015 of the three major fertiliser components: Nitrogen (N), Phosphorus (P) Potassium (K). (Source: FERTASA cited in DAFF 2016)

However, caution must be taken as numerous studies have found that even if AD can reduce microbial pathogens, the digestate may still not be completely safe to use as fertiliser (Parawira 2009, Bond and Templeton 2011, Surendra *et al.* 2014). It is essential that proper post-treatment of digestate is required prior to application as a soil conditioner/amendment to ultimately prevent public health risks (Surendra *et al.* 2014). Examples of digestate post-treatment methods are drying, composting, acticated sludge treatment, membrane filtration, ammonia stripping, and vacuum thermal stripping on manure (Trémier *et al*. 2013, Törnwall *et al.* 2017).

It is evident that there is a looming potential for biogas digester fertiliser production and use in South Africa and that it is clearly something that the government and farmers should look into as it contributes to a more sustainable farming approach for the country, not only in the ecological sense, but also on economical and sociological levels.

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PAPER 1: INVESTIGATING THE POTENTIAL OF BIOGAS GENERATION IN SOUTH AFRICA AS A SUSTAINABLE PRACTICE, BY TAKING INTO ACCOUNT THE STATUS, CHALLENGES AND OPPORTUNITIES OF THE LOCAL INDUSTRY

Abstract

Biogas generation and utilisation has the potential to impact all three pillars of sustainability namely environmental, social and economic, and could achieve what few other renewable energy technologies do, which is to integrate waste management and energy technologies (Biogas 2013, Bachmann 2015, SAGEN and SABIA 2016). For the purpose of investigating the potential of biogas generation in South Africa as a sustainable practice, a literature review was conducted, supported by face-to-face semi-structured interviews (Babbie and Mouton 2001), with among others representatives of the South African Biogas Industry Association (SABIA) and GreenCape. This investigation indicated that the interest in the development of medium and commercial-scale biogas digesters can be attributed to opportunities that the biogas industry offer in terms of job creation, energy provision, carbon mitigation, organic fertiliser production and waste management. The study found that the South African industry is currently faced with challenges in terms of renewable energy generation and supply, lack of government support, financial commitments involved in its development, skills shortages, ethical challenges, limited water resources and sustainable access to waste as a biomass source. The study also identified that innovative enablers exist that can promote the growth of the industry. In further support of its potential, biogas generation can be a means to overcome energy poverty and could contribute significantly to sustainable development in South Africa. By applying enabling factors such as streamlining EIA processes and licencing requirements and creating a market for surplus energy generated, biogas generation can provide tax relief through the anticipated implementation of carbon tax; creating innovative solutions for waste management and the organic fertiliser industry, while delivering ecosystem services such as carbon sequestration in soils and improved water and soil quality and, ultimately, an increase in food production.

Introduction

With a global drive towards a more sustainable future, two of the most significant man-induced hindrances to overcome are unsustainable management of waste and access to a secure supply of clean energy (SAGEN and SABIA 2016).

Biogas utilisation could potentially impact all three pillars of sustainability, namely environmental, social and economic, and for this reason sustainability is defined in this paper as: "*The process of utilising and living within the limits of available physical, natural and social resources in ways that promote social, ecological and economic sustainability all at the same time, while allowing the living systems in which humans are rooted to flourish in perpetuity*" (UN 1987, DEA 2008, Nahman 2009, Kuhlman and Farrington 2010, Morelli 2011, Uwosh.edu 2017, Greencape 2017).

Biogas production via anaerobic digestion could achieve what few other renewable energy technologies do as it integrates waste management and energy technologies (Biogas 2013, GreenCape 2017b), and in so doing creates a promising pathway towards achieving sustainable development. Biogas generation could ultimately reduce methane and carbon dioxide, while addressing the social dynamics and requirements of a developing country; promoting ways to reduce energy costs, provide waste management solutions and produce organic fertiliser for own use or as an additional source of income (Biogas 2013).

In this paper, the potential of biogas utilisation in South Africa is evaluated against the principles of sustainability, taking into account the status, challenges and opportunities that the industry presents.

Materials and methods

For the purpose of investigating the potential of biogas generation in South Africa as a sustainable practice, face-to-face semi-constructed interviews (Babbie and Mouton 2001), were conducted with among others representatives of the South African Biogas Industry Association and GreenCape, a non-profit organisation that drives the widespread adoption of economically viable green economy solutions from the Western Cape. This information is supported by the findings of a literature review.

1.0 Sustainability in South Africa

In 2008, South Africa adopted the National Framework for Sustainable Development (NFSD) that expresses the country's vision for sustainable development and identifies strategic interventions to re-direct South Africa's development path (DEA 2008). In response to growing pressures on the environment and its natural resources, the NFSD commits South Africa to a long-term programme of resource and impact decoupling and identifies principles and trends regarding sustainability, as well as actions to be taken (DEA 2013). Decoupling refers to the ability of an economy to grow without the parallel increases in environmental pressure. Key to NFSD is how this can be done through joint ventures and cooperative governance practices (DEA 2013).

South Africa has a systems approach to sustainability, which is one where "…*the economic system, the socio-political system and the ecosystem are embedded within each other, and then integrated through the governance system that holds all the other systems together in a legitimate regulatory framework. Sustainability implies the continuous and mutually compatible integration of these systems over time. Sustainable development means making sure that these systems remain mutually compatible as the key development challenges are met through specific actions and interventions to eradicate poverty and severe inequalities*" (DEA 2008, DEA 2013, DEA 2016). With the acknowledgement of the critical importance of moving towards more sustainable development in South Africa, the use of anaerobic digestion (AD) to generate electricity and to manage waste production could play a defining role in sustainable development (Biogas 2013, DEA 2013, GreenCape 2017a, Tiepelt 2017). GreenCape (2017a) regards the development of biogas industry as based on the triple bottom line context of an African economy; measuring the impact of an investment in technology on its social, environmental, and economic relevance and its relation to the concept of sustainable development (Hammer and Pivo 2016).

2.0 Development of the biogas digester industry in South Africa

For a long time the South African biogas industry existed in a low-intensity state, a fact that could be seen as evidence of its potential (SAGEN and SABIA 2016). The first example of a biogas digester in South Africa was on a pig farm south of Johannesburg in the early 1957. This was done by John Fry, who started producing biogas through using pig manure in very simple 170 litre drums as digesters to run his six horsepower Lister engine (GIZ and SALGA 2015a).

While the Department of Energy (DoE) admits to the limited existence of both domestic and commercial applications in South Africa (DoE 2015), South Africa was again one of the first countries in the world to develop digesters as part of sludge management at waste water treatment works (WWTW), with the first municipal digesters built as far back as in the 1940s (GIZ and SALGA 2015a).

However, these were isolated incidences. Compared to other developed and developing countries, South Africa has had a slow uptake of anaerobic digestion, both commercially and rurally. Government-funded rural biogas implementation such as is seen in China and India (also BRICS countries), has not been applied in South Africa, mainly due to intensive capital investment requirements, slow and hindering legal processes and a lack of government support (SAGEN and SABIA 2016).

In the late 1970s and early 1980s digesters were put to more active use at WWTWs. In 1998, the Ceres Fruit farm digester was built followed by the Cape Flats biogas digester for dewatering sludge in 2003 and the completion of a 1.5 MW digester at Marianhill in Durban in 2010 (Mutungwazi *et al.* 2017). But, the focus was on sewage/sludge management and not on the production of biogas, as the primary aim of the water works was to treat water, while the digestion process provided an easy way to reduce the quantity and improve the quality of the sludge. Here biogas was vented or burned as a by-product. While some plants used it to incinerate all large particles removed from the waste water and others used the gas to heat up the digesters, it was never really used to generate electricity (Tiepelt 2017). GreenCape (2017a) maintains that while the majority of South African WWTW have anaerobic facilities, the methane gas is mostly vented.

Tiepelt (2015) stated that a total of 700 digesters existed at the time; 40 % at wastewater treatment works, 50 % small-scale domestic/rural digesters and that only 10 % were commercial installations (SAIREC 2015). ESI-Africa (2016) contradicted this by reporting a total of 300 registered biogas plants in 2016, of which only 50 were registered commercial biogas plants larger than 100 kW. This indicated that the country’s biogas industry comprises a growing number of privately funded projects on agricultural land with livestock, at abattoirs, municipal wastewater treatment plants and in rural/domestic households (See Table 1). GreenCape (2016, 2017a) support this by stating that the main waste-to-energy projects embarked on by the private sector are on a small to medium-scale, where the energy (electricity, heat and/or gas) is generated for own use, or wheeled through the grid to a nearby private buyer.

Table 1 shows the list of biogas digesters installed in different parts of South Africa by different developers. These power output values give a close estimation of the biogas yield achieved by a given digester since 1 m^3 of biogas generally produces 6 kWh of chemical energy (Arbon 2005, Biogas 2013, Mutungwazi *et al.* 2017).

Taking into account the slow but progressive movement towards renewable resource incentives in South Africa, biogas power generation is now presenting a strong business incentive (GIZ and SALGA 2015). The South African Local Government Association (SALGA) and the South African-German Energy Programme (SAGEN), implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), entered into an agreement to promote renewable energy at the local level of government. The collaboration aims to strengthen the capability of local government to implement renewable energy projects and to promote the facilitation of these projects within their areas of jurisdiction (GIZ-SAGEN 2015).

The Northern Waste Water Treatment Works (WWTW) of Johannesburg Water is an example of this collaboration. Facing a steep increase in energy costs, Johannesburg Water commissioned the upgrading of its sludge handling and digestion facilities at its five waste water treatment plants to provide for the cleaning of biogas to use in electricity generation by means of cogeneration methane gas engines. The initial installation at the Northern WWTW was completed in 2012 and is capable of producing 1.1 MW of power for the treatment plant, representing 18 % of the plant's power requirements at the time (GIZ and SALGA 2015a).

Table 1: Illustrates location, developer name, substrate input and power output of biogas digesters installed in South Africa (Source: GreenCape 2017c, Mutungwazi *et al.* 2017)

Area	**Developer**	**Substrate input**	**Power output**
Alice in the Eastern Cape	CAE/University of Fort Hare	4 000 m^3 of dairy and piggery manure	2 × 132 kVa electricity generators
Athlone Industria	Alrode Brewery, Farm Secure Energy, Wastemart, CEA/New Horizons waste to energy	400 t of organic waste/day	-
Bela-Bela Limpopo	CAE Humphries Boerdery piggery	Manure and waste water	-
Belville	EnviroServ	Waste water treatment plant	-
Bonnievale	FarmSecure Carbon	> 5 t bovine manure	-
Bredasdorp	iBert	4 t abattoir waste/day	100 kW
Cavalter	iBert, EnviroServ/ Chloorkop LFG,	20 t abattoir waste/day	500 kW
	Cullinan	-	190 kW
Darling Uilenkraal	CAE/Uilenkraal dairy farm	Bovine manure	600 kW
Darling GrootPost	FarmSecure manure	Bovine manure	-
Durban	Bisasar road LFG	3 500–5 000 refuse/day	6 MW
	Marrianhill LFG, Ekhurleni LFG	550–850 t/day	1,5 MW

Area	**Developer**	**Substrate input**	**Power output**
Grabouw	Elgin Fruit and Juices, Ibhayi Brewery	> 5 t of fruit waste/day	500 kW
Jan Kempdorp	iBert	5.5 t abattoir waste/day	135 kW
	Jacobsdale	-	150 kW
Johannesburg	WEC/Northern Waste Water Treatment Works	Sewage sludge	1,2 MW
Johannesburg	Robinson Deep	-	19 MW
Klipheuwel	Reliance Composting	700 t organic waste/day	-
Klipheuwel (Zandam)	Farmsecure	> 5 t of manure/day	600 to 700 kW
Mossel Bay	Biotherm SA, Mossel Bay PetroSA	Refinery waste water	4,2 MW
Newlands	SAB Miller	4 500 m^3 of wastewater/day	10 % of the plant's energy demand
Paarl	Drakenstein Municipality	-	14 MW
Pretoria	Bio2watt / Bronkhorstspruit Biogas plant, Prospection Brewery	Manure	4,6 MW
Queenstown	iBert	42 t mixed waste from a piggery/day	-
Riversdale	iBert	4 t abattoir waste/day	100 kW
Robertson	Rosslyn Brewery	-	150 kW
Springs	BiogasSA / Morgan Springs	Abattoir slaughter waste; organic waste	0,4 MW

Area	Developer	Substrate input	Power output
Stellenbosch	Veolia Water Technologies / Distell	1 000 m^3 wastewater/day	-
Stellenbosch Franschhoek	Rhodes Food Group	35 kg per day (testing feedstock)	-
	Selectra	Sewage, manure, fodder	0,5 MW
	Selectra	Sewage, manure, fodder	1 MW
	Selectra	Sewage, fodder, agricultural waste	1 MW
Table View	Jeffares and Green / Bayside Mall	0,6–1 t of food waste/ day	-
KZN	Khanyisa projects	Manure from more than 2 cows, school, organic and sewage waste	Rural cooking fuel
	SANEDI	Manure from more than 2 cows, school, organic and sewage waste	Rural cooking fuel
Eastern Cape (Alice, Fort Corx and Melani villages), Western Cape (Phillipi), KwaZulu-Natal	AGAMA	Manure from more than 2 cows, school, organic and sewage waste	Rural cooking fuel
Gauteng	Zorg	Vegetable pulp and fodder	7 200 m^3 methane

Tiepelt (2017) regards the Bronkhorstspruit Biogas Plant erected by Bio2Watt as the biggest biogas project in Africa at a feedlot. Established in 2007, and awarded the South African National Energy Association award for an energy project in 2015, Bio2Watt aims to produce in excess of 50 MW of green energy in the country over the next ten years (Bio2Watt.com 2017). This company owns and operates the Bronkhorstspruit Biogas Plant (Pty) Ltd that first contributed power to the national power grid in October 2015. It is regarded as an independent commercial enterprise with an initial life cycle of 20 years, contributing to South Africa's energy mix. Its installed capacity is 4 MW (Bio2Watt.com 2017).

Biogas production in South Africa received a lot of attention up until 2013, followed by a slight loss of momentum possibly due to both the policy and legislation hindrances and a shift of interest towards solar and wind power. However, interest increased again during 2016 with the new National Biogas Strategy 2015/2016 that had been drafted by the Department of Energy (DoE 2016).

In January 2017, the Industrial Development Corporation (IDC), Clean Energy Africa, WasteMart and Afrox, launched the multi-million rand New Horizons waste-to-energy plant in Athlone, Cape Town (GreenCape 2017c). The plant will process over 500-600 tonnes per day of municipal solid waste, amounting to about 10 % of the waste generated in Cape Town (GreenCape 2017c, SAOGA 2017). This will be recycled and converted into various products, including organic fertiliser, liquid carbon dioxide (CO_2) and compressed bio-methane (SAOGA 2017). According to Tiepelt (2017), these developments are indicative of the growing interest in the commercial and large-scale use and implementation of biogas seen in South Africa in the last five to six years. He ascribes this not to available incentives or government rebates/subsidies, but to the tenacity of some project developers, combined with the fact that many abattoirs and waste producers in South Africa face problems getting rid of their waste.

Tiepelt (2017) believes that biogas generation at abattoirs, piggeries and feedlots in the country can be seen as a waste management solution rather than a financial viable replacement for Eskom bought electricity. This is supported by the GreenCape Market Intelligence Waste Economy Report (2014) that states that the growth of small-scale biogas projects in South Africa can be attributed to stricter environmental legislation regarding waste disposal, and higher landfill fees coupled with the premium tariffs offered by Eskom (AltGen, GIZ, SAGEN and GreenCape 2014).

SAGEN and SABIA (2016) reported that the rural sector has significant biogas potential due to the fact that many communities are still without access to electricity, and even those with electricity would prefer to use more cost-effective alternative fuel sources. The total potential of electricity generated from biogas in South Africa from agricultural waste is estimated at 2 300 MW (GreenCape 2016), and it is predicted by Abbasi (2012) that by 2020, the largest volume of biogas will come from farms and large co-digestion plants that are incorporated into farming and food-processing structures. Households with enough waste or livestock are also able to implement biogas digesters to generate an alternative energy source for heating (Amigun *et al*. 2012).

There are several developers and governmental programmes implementing biogas projects within the rural sector (see Table 1). The South African National Energy Development Institute (SANEDI) is currently implementing the Working for Energy Programme, an initiative focused on providing thermal energy and improving the quality of life in rural communities. They are involved in three renewable energy initiatives, including the Melani Village Biogas Expansion Project, the Illembe District and Mpufuneko Biogas Projects (SAGEN and SABIA 2016). The lllembe District Biogas Project in KwaZulu-Natal has 26 operational digesters, and the Mpfuneko Biogas Project in Limpopo will comprise the installation of 55 digesters. The Melani Village Biogas Project in the Eastern Cape has been jointly developed with the University of Fort Hare, aiming to install 110 animal manure-fed biogas digesters in the rural areas of the Eastern Cape specifically in villages around the University of Fort Hare's Alice Campus (UFH 2017). The specific focus is on making energy more accessible and affordable to disenfranchised communities, and would thus enable the villagers of Melani Village to use cheap and convenient biofuels. The project is an ongoing and funded by the Department of Energy (DoE) by some R3.7 million through SANEDI, their subsidiary (UFH 2017).

A number of developers are also active in the rural/small-scale sector including BiogasPro, Agama and BiogasSA (SAGEN and SABIA 2016). Other small-scale digesters that have been in operation before 2013 include a CAE installation of 30 kW at Humphries Boerdery (Bela-Bela), and iBERT installing four small-scale biogas digester; Abattoir-Jan Kempdorp (100 kW), Cullinan (190 kW), Robertson (150 kW) and Jacobsdal (150 kW). BiogsaPro Agama has installed 320 small-scale units to date. Their projects are mostly located in the Western Cape with some in the provinces of the Eastern Cape and KwaZulu-Natal (SAGEN and SABIA 2016).

3.0 Biogas potential in terms of energy demands and waste management in South Africa

3.1 Biogas generation as a strategy to address energy demands in South Africa

The Department of Energy (DoE) is assigned to ensure the sustainable and secure delivery of energy for South Africa's socio-economic development. Its National Development Plan (NDP) foresees that South Africa will, by 2030, have an energy sector that promotes economic growth and development through sufficient investment in energy infrastructure. It anticipates that at least 95 % of the populace will have access to grid or off-grid electricity. The intention is that gas and other renewable resources like solar, wind, and hydro-electricity will be present as feasible substitutes to coal, and will supply at least 20 000 MW of the additional 29 000 MW of electricity that will be required by 2030 (DoE 2015). This is imperative as the energy mix should take into account its potential environmental impact and should address sustainability by amongst others mitigating the effects of climate change (DEA 2017). The South African government has also committed to a 34 % reduction in greenhouse gas emissions by 2020 (Teljeur *et al.* 2016). GreenCape (2017a) believes that biogas generation has the potential to save on carbon emissions especially when used as an alternative fuel for operating machinery.

Since 2007 and until August 2015, South Africa had faced an unprecedented supply crunch in the electricity sector that resulted in the country being unable to meet peak electricity demands (Teljeur *et al.* 2016). The World Wide Fund for Nature's (WWF) Food Energy Water (FEW) report specifies that energy is a major element in the competitiveness and sustainability of the farming sector (Carter and Gulati 2014) and unsustainable consumption and production patterns due to the recurrent electricity crisis in South Africa have resulted in huge economic and social costs for the country emphasising the need innovative use of energy sources (Teljeur *et al.* 2016). South Africa also has a very specific electricity load profile that does not necessarily match the period of highest solar energy generation, nor does wind energy profiles fit in predictably with this demand profile (Griffiths 2013). This leaves a gap for biogas electricity generation to alleviate peak hour demand. As long as the plant is maintained and correctly supplied with feedstock, generation from biogas is not dependent on any external conditions, making it a very suitable option (GreenCape 2017a, Griffiths 2013). In addition, available incentives and rebates make farm-scale biogas plants a very attractive option for farms looking to reduce their carbon footprint and save on electricity bills (Biogas 2013, Griffiths 2013, GreenCape 2017a, Scharfy *et al* 2017) while South African developers are also looking at heat generation and the production of compressed natural gas to address the needs of the growing duel fuel systems market (GreenCape 2017a).

3.2 Biogas generation as a strategy to address waste management in South Africa

The uninhibited generation of waste is an unfortunate reality in South Africa and across the world. The DEA recognises in their Environmental Outlook Report 2013 (DEA 2013) that economic development, a growing populace and increased urbanisation have resulted in the generation of so much waste that biogas digesters will be needed for its management. Waste management in South Africa still largely relies on landfills which are the cheapest waste disposal option due to low costs and availability of land, with 90,1 % of waste generated being disposed of to landfill in 2011 (DEA 2012, GreenCape 2017c). The National Environmental Management: Waste Act (No. 59 of 2008) (NEM:WA 2008) and the National Waste Management Strategy (NWMS) (2011) mandate municipalities to implement alternative waste management to divert waste from landfill and minimise environmental degradation (GreenCape 2017b).

One of the distinct advantages of a biogas plant is its ability to be located anywhere where waste feedstock is available enabling it to play a significant part in the sustainability progress of a country by contributing substantially to efficient waste management (Biogas 2013, Msibi 2015, SAGEN and SABIA 2016). This makes it particularly suitable for rural areas as the agriculture sector generates mainly organic waste that could be used as feedstock (GreenCape 2016, GreenCape 2017b).

It is estimated that in 2009, 40 % of waste generated in South Africa comprised organic matter which, when digested could supply biogas (Greben and Oelofse 2009), while the DEA in 2012 estimated that 65 % of waste (approximately 38 million tonnes) is recyclable and could be redirected from landfills to be repurposed (DEA 2012). The WWF FEW report (Carter and Gulati 2014) states that nine million tonnes of food is wasted every year (34 % of all food) and that energy lost this wastage could potentially power Johannesburg for 20 years. Inhibiting factors of this process currently are policies and legislations prohibiting the reuse of food waste in South Africa (Von Bormann and Gulati 2014).

4.0 Opportunities and benefits of biogas generation in South Africa

The potential of small to medium-scale biogas digesters (APPENDIX B) to contribute to sustainable development by providing a variety of socio-economic benefits, such as a diversification of energy supply, enhanced regional and rural development, the creation of a domestic industry and employment opportunities, and a wider variety of waste management options is widely recognised (Rio and Burguillo 2008, Mshandete and Parawira 2009, NERSA 2013, SAGEN and SABIA 2016, BiogasSA 2017, GreenCape 2017a). Small-scale biogas digesters are also shown to especially beneficial in rural areas of southern Africa where poverty levels are very high and where organic waste is generated that could be used as a potential feedstock (Smith 2011, Amigun *et al.* 2012, GreenCape 2016, GreenCape 2017a). Ecosystem services that are potentially delivered in these rural communities are increased carbon sequestration in soils altered with digested organic waste, improved water quality, reduction of pollutants, and ultimately an increase food production (Ji-Quin and Nyns 1996, Mtambanengwe and Mapfumo 2005, Fonte *et al.* 2009, Onwosi and Okereke 2009, NERSA 2013). Indirect carbon sequestration can also be attained through reduced carbon losses due to reduced deforestation when household fuel is substituted by methane produced AD (Lantz *et al*. 2007, Mwakaje 2008).

Many of these benefits are directly relevant to the Millennium Development Goals of reducing poverty, promoting gender quality, promoting health and environmental sustainability (UN 2015) and ties in with the Sustainable Development Goals (see APPENDIX A) of the United Nations Development Programme (UNDP 2017).

4.1 Meeting rural energy needs and enhancing quality of life

Biogas has significant potential to meet South Africa's energy needs through amongst others simple installations in rural areas that could produce enough energy for cooking and heating, and could be expanded to community-based or commercial biogas generation efforts (Biogas 2013, GreenCape 2017a). Installations such as these can lead to reduced levels of indoor smoke, better lighting and creation of employment for local people (Amigun and Von Blottnitz 2010). Msibi (2015) states that the complete substitution of fuel wood as a source of energy with biogas could result in cost savings of R1 808 per household per year, which is 8,6 % of the household income and translates to a gross national annual cost saving of up to R4-5 billion. The potential for the improvement of human well-being is thus significant.

4.2 Incentives and rebates in renewable energy generation

Policy and legislation has been a heated point of discussion in the field of biogas in South Africa, especially with the implementation of tax rebates in the renewable electricity generation with great disputes between the solar, wind and biogas electricity generation fields (Camco Clean Energy 2012, NT 2013, NT 2014, NT 2015, SAGEN and SABIA 2016).

ESI-AFRICA (2016) states that the prevailing biogas feed-in tariff and a positive swing in current environmental legislation which encourages the establishing of biogas plants, i.e. the National Environmental Management Act (NEMA), the National Environmental Management: Waste Act (NEM:WA), the National Environmental Management: Air Quality Act, the National Waste Management Strategy (NWMS) and the Income Tax Act Amendment 12L (Cleaner Development Mechanism) all serve to create conditions that stimulate local biogas producers and may attract foreign biogas producers to the South African market. The establishment of the Southern Africa Biogas Industry Association (SABIA) further emphasises the expectation of the growth of the biogas industry in the country (ESI-AFRICA 2016).

On a commercial and industrial scale, ESI-AFRICA (2016) projects that biogas generation in South Africa has the potential to displace 2 500 MW of grid electricity, which is equal to the size of Eskom's Arnot coal-fired power station in Mpumalanga that was commissioned in 1975. According to The Market Intelligence Report (GreenCape 2016) biogas provides heating and electricity generation potential with a current market value of more than R450 million, and a potential market of R18 billion; compared to solar-thermal which currently has an industrial-scale installations value of about R100 million and a R3,7 billion potential market for agri-processing in South Africa.

The joint rebate programme of Eskom and the Department of Trade and Industry (DTI) together with the grants and better interest rates from the Industrial Development Corporation (IDC) that provides for a low prime loan for green technology investments (Griffiths 2013, Ruffini 2014, Tiepelt 2017), substantially enhanced the financial feasibility of biogas projects in South Africa (GreenCape 2017c).

Furthermore, the Eskom Integrated Demand Management (IDM) offers an incentive for reduced consumption under their Standard Offer Programme (SOP). In 2013, the IDM proposed that for every kWh generated by a biogas plant in South Africa between 18h00 and 20h00 weekdays for the first three years of operation, Eskom will contribute R1.20 (Ruffini

2014). While this is not a big contribution to small-scale digester owners as their kWh production is much lower than large-scale plants, it could play a role in the alleviation of poverty by promoting domestic well-being through the growth of small-scale digesters as seen in Asia (Zhu 2006, Bond and Templeton 2011, Smith 2011).

4.3 Carbon mitigation potential

Opportunities that are created for carbon mitigation are seen as one the key benefits and motivations for the development of the biogas industry in South Africa (Tiepelt 2017). South Africa is responsible for approximately 1.1 % of global greenhouse gas (GHG) emissions and its emissions have increased by 24.9 % between 2000 and 2010 (Biogas 2013). Although the waste sector adds only about 2 % to the total GHG emissions, it also presents a chance for energy recovery and improved waste management practices (DEA 2010).

South Africa is a signatory to the Kyoto Protocol and the Paris Agreement and has agreed through the adoption of its National Climate Change Response Policy in 2011 to implement mitigation measures (reducing greenhouse gas emissions) and adaptation measures (ensuring climate-change resilience through public investments) to reduce greenhouse gas emissions by 34 % in 2020 and 42 % in 2025, subject to certain conditions (NT 2014).

The implementation of carbon tax is an important component of this mitigation policy. National Treasury published the Draft Carbon Tax Bill for comment in November 2015 with the intention that carbon taxes would be implemented in a phased manner with effect from 1 January 2017 (NT 2014, NT 2015, Martineau 2017). The purpose of the 2015 Draft Carbon Tax Bill is to address climate change and to facilitate a viable transition to a low-carbon economy by combating GHG emissions, but also taking advantage of new investment opportunities (NT 2015).

An analysis of mitigation potential by the Department of National Treasury shows that the following focus areas could be eligible for projects (NT 2014):

- Energy and energy efficiency with reference to energy efficiency in household and commercial sectors, small-scale renewable energy, community-based and municipal energy efficiency, renewable energy fuel-switching projects and electricity transmission and distribution efficiency.

- Agriculture, forestry and other land uses with specific reference to anaerobic biogas digesters.
- Waste management with reference to municipal waste.

Biogas schemes are also entitled to Clean Development Mechanism (CDM) rebates as they remove methane production from the atmosphere; especially taking into account that methane is up to 30 times more effective as a greenhouse gas than carbon dioxide (Ruffini 2014, Atkins 2017). CDM mechanisms are evolving continuously, also allowing the pooling of a number of small projects to gain credits - a model that is very suitable to biogas digestion.

It is estimated that the average reduction in emissions that could be realised between 2013 and 2032 from the CDM projects registered as of November 2012 equals 17.2 million tonnes CO_2 per year as shown in Table 2 addressing the following sectors: biogas, biomass, energy efficiency, fuel switch, methane recovery and utilisation and waste gas/heat recovery (Camco Clean Energy 2012, NT 2014).

Table 2: CDM credits expected to be issued in South Africa per project type. (Source NT 2014)

Sector	**Certified Emission Reduction (CERs)**
Biogas	103 672
Biomass	881 144
Energy efficiency	398 098
Fuel switch	1 662 205
Hydro power	169 693
Methane recovery and utilisation	1 694 461
N_2O decomposition	2 164 037
Waste gas/heat recovery	1 945 559
Wind	7 561 841
Solar photovoltaic	473 624
Concentrated solar power (CSP)	230 537
Total	**17 284 871**

Tiepelt (2017) believes that the carbon mitigation potential of the biogas industry gives export companies a competitive advantage in overseas markets where the carbon footprint of the company is required. GreenCape (2017a) however states that currently no official sustainability accreditation exists, and that investors are not necessarily motivated by the potential of the development to contribute to sustainability but are rather driven by the purpose of the project be it electricity generation or waste management. Atkins (2017) confirmed that tax incentives would not exist in South Africa until the carbon tax is indeed implemented.

4.4 Efficient waste management

While SAGEN and SABIA (2016) reports that currently the South African biogas industry is mainly used to solve waste management problems by redirecting solid and hazardous waste away from landfills, biogas generation also presents an alternative renewable energy resource especially in rural areas as it can be located wherever waste feedstock is available, making it particularly suitable for rural areas (Amigun *et al.* 2012).

Potgieter (2011) referred to the potential of biomass as renewable energy resource as the combined energy value of all the various biomass types available that can realistically be converted into bioenergy, and found that the potential of biomass as renewable energy resource exceeds the annual primary energy consumption of the world. Other investigations into the available waste streams show that there is potential to implement many more anaerobic digesters nationwide, particularly as a cost-saving measure where waste can be diverted from landfills or re-used as a source of heat or energy (Barnard and Holzbaur 2013, GreenCape 2017b, GreenCape 2017c).

Government rebate programmes are in place as part of the Waste Management Flagship Programme (WMFP*)* and states that *"the Department of Environmental Affairs will determine the GHG mitigation potential of the waste sector and investigate the opportunities for waste-to-energy conversion practices, as well as the production and capture of methane or landfill gas from waste sites. This information will be used to develop and implement a detailed waste-related GHG emission mitigation action plan, and detail appropriate policies for facilitating its implementation*" (NT 2013). While internationally government-initiated programmes supports the use of many more feedstock avenues on a large scale, there is still much potential for such government-initiated programmes in South Africa (SAGEN and SABIA 2016).

Green fuels are well developed in Sweden and India, where many taxis are already running with the use of gas bottles, while relatively undeveloped in South Africa (Biogas 2013). According to Raoul Goosen (Industrial Development Corporation's Green Industries Business Unit), vehicular biogas also provides an important waste management opportunity since one tonne of bio-waste is equal to the equivalent of 1 000 litres of petrol and 1 000 km of CO_2 neutral drive (3SMedia 2013). GreenCape (2017a) believes that the growth in duel fuel transportation systems will further stimulate the biogas market.

4.5 Utilisation of digestate as organic fertiliser

There is sufficient scientific and practical evidence of the capability of digestate to act as a soil conditioner and to enhance plant growth and yields (Dennis and Burke 2001, Dillon 2011, Torquati *et al.* 2014, Msibi 2015, SAGEN and SABIA 2016, Culhane 2017, GreenCape 2017a, Tiepelt 2017). South Africa is a net importer of fertilisers, importing all its potassium, as well as 60 % to 70 % of its nitrogen requirements (Figure 1).

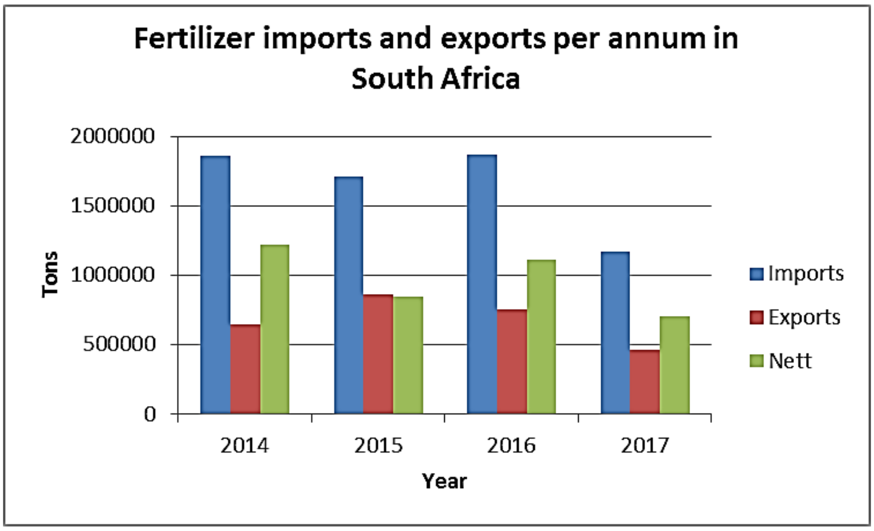

Figure 1: Fertiliser imports and exports per annum in South Africa from 2014 to 2017 (Source: FERTASA 2017). This information is regularly updated by the Fertiliser Association of South Africa (FERTASA), thus the tonnage for 2017 is valid for the date that it was sourced; 2nd October 2017).

In this deregulated market environment, fertiliser prices are strongly influenced by international prices, currency exchange rates (ZAR/USD) and shipping costs (DAFF 2015).

The use of digestate as potential supplement for specific mineral nutrients provides economic and environmental advantages. Guatam *et al.* (2009) found an annual savings of 4 329 T N, 2 109 T of phosphorus and 4 329 kg potassium due to the installation of biogas digesters in Nepal that replaced previously imported chemical fertilisers with the organic form of digestate fertilisers. An additional major benefit is that the digestate produced from a biogas digester can be considered as an organic fertiliser rendering it suitable for soil improving (Makádi *et al.* 2012, Tiepelt 2017). By contributing to the direct carbon sequestration through the use of organic material sourced from the digested matter, carbon can also be directly sequestered in the soil (De Neve *et al.* 2003). The increased application of organic matter reduces erosion and stabilises sandy soils further improving water quality (Yongabi *et al.* 2009).

However, GreenCape (2017c) found that in South Africa a difficulty in finding offtakers for digestate exists and that mechanisms are needed to concentrate the digestate and reduce the volume, which links to lower logistic and handling costs.

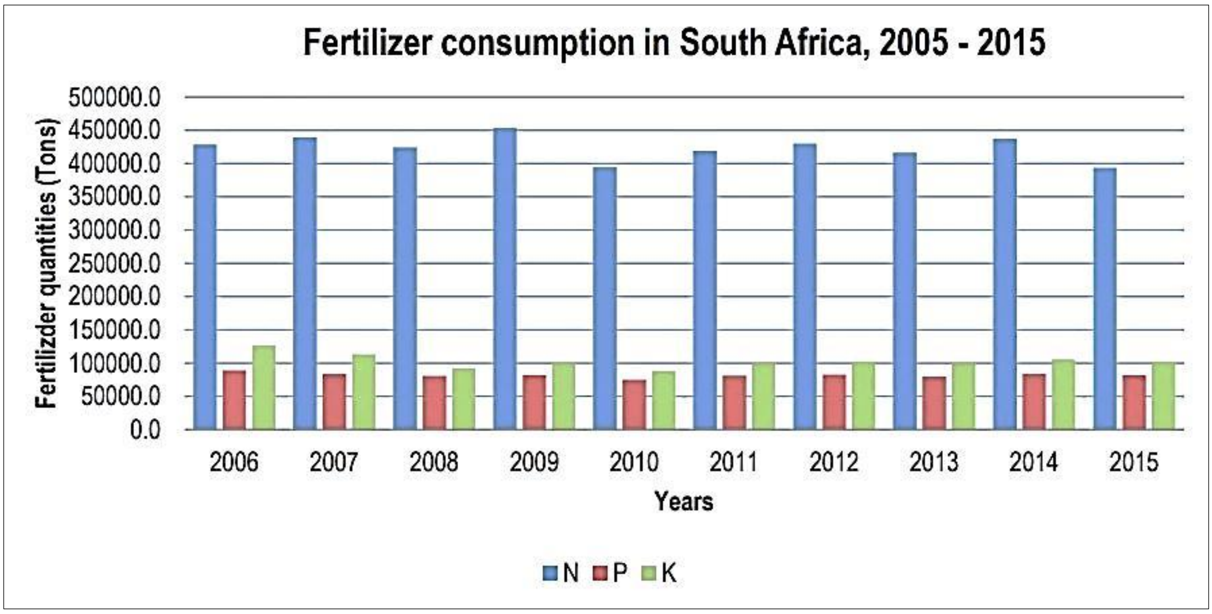

Figure 2: Fertiliser consumption of nitrogen (N), phosphorus (P) and potassium (K) in South Africa per annum from 2005 to 2015 (Source: DAFF 2016)

4.6 Job creation

Probably the most important consideration when promoting the biogas industry is its potential to create jobs (SAGEN and SABIA 2016). A recent study on opportunities for job creation in renewables compared the government's current pathway based on the 2011 Integrated Resource Plan for electricity (IRP), to the Green Peace Advanced Energy Revolution (GPAER). The IRP will result in 111 000 direct jobs by 2030, compared to 149 000 direct jobs in the GPAER (GreenPeace 2011). Ruffini (2014) estimated that biogas as a renewable energy source could lead to five times more permanent job opportunities than what is available in solar energy. GreenCape (2017c) estimated that based on its potential, job creation is estimated at 320 to 3950 direct jobs, at a job intensity of 4 – 10 jobs per megawatt (MW) of installed electrical capacity.

5.0 Challenges and enablers of the South African biogas digester industry

Obtaining renewable energy through biogas generation could be particularly complex, (Torquati *et al.* 2014). GreenCape (2017a) believes that the many variables in the South African scenario complicates implementation as there is no single solution applicable to most as is often found to be the case in Europe, and that implementation here should be site-specific to succeed. Lack of government involvement and motivation to support biogas production is a drawback for the industry (GreenCape 2017c) and Tiepelt (2017) argues that the biogas industry cannot establish itself in any country in the world without a source of subsidy.

Challenges in South Africa do not lie in the development of the biogas digesters but translational research is needed to make it possible for digesters to be locally produced, and implemented in an effective, safe and affordable way with specific reference to South African circumstances (Terreblanche 2002, Woolard and Leibbrandt cited in FAO 2004, Smith 2011, Ruffini 2014, GreenCape 2017a, GreenCape 2017b).

5.1 Lack of awareness

Enabler: While current lack of awareness of biogas digesters in the public sector, private sector and government curbs the potential of the industry, an enabling factor in this regard is the contribution of SABIA, industry stakeholders and industry to create increased understanding of the potential of the industry (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017).

5.2 Regulatory and time constraints

A full environmental impact assessment (EIA) is required for the establishment of all plants that produce methane (AltGen, GIZ, SAGEN and GreenCape 2014, GIZ-SAGEN 2015, SAGEN and SABIA 2016, Tiepelt 2017). To fulfil these environmental licensing requirements are time consuming and not cost effective (GIZ-SAGEN 2015, Tiepelt 2017).

Tiepelt (2017) regards the amount of time spent to implement endeavours is a major challenge in South Africa. The Bronkhorstspruit project took about seven years from initialising the project, to the start of the building process, and another 18 months to build the plant (Bio2Watt.com 2017).

In addition, long-term supply contracts for waste facilities pose a problem as most waste-to-energy facilities have a payback period of 15-20 years, and, to attract investors, could require contracts of the same length for the feedstock. This has proven challenging for South African companies that target municipal solid waste as municipalities typically have three to five-year procurement contracts (GreenCape 2016, Tiepelt 2017).

Enabler:

- Streamlining EIA processes and making provision for requiring less licencing for plants with lower output could enable the development of the industry (GIZ-SAGEN 2015).

5.3 Electricity wheeling arrangements and supply

Another major factor in curbing the advancement of the industry is the wheeling agreement between the power generator and the owner of the grid – either Eskom or the local municipality (GreenCape 2017c, Tiepelt 2017). In the case of the Bronkhorstspruit project, power had to be wheeled from Bronkhorstspruit, through the Eskom grid, to the Tshwane grid, and then from the Tshwane municipality to the BMW site in Rosslyn Pretoria which acts as the off-taker of the electricity.

In terms of electricity supply and demand, farmers in South Africa are faced with the challenge of excess electricity (Tiepelt 2017). In Europe, farmers may generate electricity 24/7, and after using what they require, supply the excess electricity to the national electricity grid. In South Africa, however, excess energy cannot be fed to the national electricity grid, which means that a farmer has to be able to use 90 % of the electricity generated to make his project viable and financially sound (Tiepelt 2017). GreenCape (2016) adds that further constraints include the lack of feed-in tariffs for renewable energy outside of the REIPPPP (which only applies to projects larger than 5 MW) as well as the lack of a policy/regulatory framework for grid connection by independent power producers outside of the REIPPPP.

In addition, electricity prices as compared to developed countries are still low (although the cost of electricity is escalating quickly), and waste-to-energy is still proving to be more expensive (R1.40-R1.60 /kWh) compared to bulk electricity prices (R0.50-R0.90 /kWh more on average) (GreenCape 2016, GreenCape 2017a). GreenCape (2017c) found that although the intent of the REIPPPP was to encourage waste-to-energy projects as well, no biogas projects have been successful in the various bidding rounds for utility scale renewables.

Taking this into account GreenCape (2017a) believes that at this stage it does not pay biogas plants to feed electricity into the grid, and that electricity generated should be used on site or sold at a premium.

***Enablers**:*

Small-scale embedded generation (SSEG) tariffs would enable biogas facilities to supply electricity generated through wheeling operations, where the electricity is not sold to Eskom or the Municipality but through a power purchase agreement with a business entity. Frameworks for wheeling arrangements are under development at certain municipalities (GreenCape 2017a).

- Exemption from electricity generation licences are expected to be Gazetted soon which will enable generation for own use on site, for back-up storage, for pilot projects, for off-grid use and for wheeling for single use without requiring a licence (GreenCape 2017a).
- GreenCape (2017a) foresees that municipalities will in the near future be able to buy electricity from any independent power producer and not only Eskom, awaiting government approval. Creating a market for surplus energy generated by plant with a capacity of <1MW, could enhance the potential of the biogas industry (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017).
- Electricity trading will enable third party traders to buy excess energy from Eskom or municipalities and sell it to clients. This will assist municipalities who have reached their demand (GreenCape 2017a).

5.4 Financial requirements

Karekezi (2002) noted that practical problems in biogas project developments include unaffordable initial investment costs. Tiepelt (2017) together with GreenCape (2017c) argues that financial viability remains the biggest test to the South African biogas industry. GreenCape (2017c) stated that overall in the South African context, financial viability of biogas projects is highly site-specific and only strong under certain conditions. GreenCape (2017c) further states that failure of projects in South Africa has primarily been due to unfavourable cost-benefit ratio, often as a result of insufficient scale, and particularly when electricity generation was not utilised, or could not be utilised as envisioned (e.g. fed into the grid). SAGEN and SABIA 2016 states that high capital costs and lack of remuneration mechanisms for electricity generation <1 MW as a hindrance. This is sustained by GreenCape (2016) identifying the lack of feed-in tariffs for renewable energy outside of the REIPPPP, which only applies to projects larger than 5 MW as a challenge. Current tight capital margins further inhibit the industry to appoint and remunerate qualified plant operators (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, GreenCape 2017c, Tiepelt 2017).

Taking the current Eskom tariff together with the escalation of the Eskom tariff over the next five years into account, biogas plants may only break even after approximately 4-5 years, and start to pay back after 7-10 years, making it not readily viable on a farm-scale if the motivation to implement biogas digesters is primarily based on a pay-back return point (GreenCape 2016, Tiepelt 2017).

The Department of Trade and Industry (DTI) have an incentive programme MCEP (Manufacturing Competitive Enhancement Project) (ESI-AFRICA 2016), which farmers can apply for, but it has been over-subscribed, making it currently inaccessible for farmers (DTI 2015, Creamer 2016, Tiepelt 2017). All new applications for the MCEP were suspended in October 2015, reportedly necessitated by a lack of funds as the more than R5 billion set aside for this programme was fully committed (DTI 2015). According to Creamer (2016), the new application window was set to open in April 2016 but is delayed due to inadequate funding. While the agriculture sector implored the DTI to continue with the MCEP, full reactivation will only happen once adequate funding is secured (Creamer 2016).

Enablers:

- The opportunity that it presents to larger corporate industries in terms of expanding green footprint production and carbon mitigation incentives, could make it financially more viable for such institutions (SAGEN and SABIA 2016, GreenCape 2016, GreenCape 2017c, Tiepelt 2017).

- ESI-AFRICA (2016) reports that there are incentives to overcome limited funding for small projects such as the Manufacturing Competitiveness Enhancement Programme (MCEP), Eskom's Industrial Demand Side Management (IDM), the Industrial Development Corporation's Green Energy Efficiency Fund, as well as foreign funding and a gradual involvement by local banks to participate in long-term biogas financing.
- Increasing waste management costs (GreenCape 2017c)
- Private-public partnerships have proved to work well in other parts of the world such as in Thailand, Nepal, India and Germany (Biogas 2013).
- More streamlined processes could potentially require less capital investments (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017).

5.5 Scale of projects

The scale of the biogas project or plant also has an impact on its potential for success. Two of biggest current participants in biogas generation are 5.5.1 municipalities and 5.5.2 farmers (Biogas 2013, Mutungwazi *et al.* 2017, Tiepelt 2017).

5.5.1 Municipalities

Municipalities are challenged by the time span of the projects. Biogas generation projects in South Africa have a long payback period of approximately 10 to 15 years (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017). Municipalities are bound by the MFMA (Municipal Financing Management Act), which only allows them to sign a contract for three years, and for longer periods they need to acquire approval from the National Treasury of South Africa (NT-MFMA 2017). This is thus found to be a hindrance because of the lingering tender process combined with the unstable economic state of the government of South Africa (Peyper 2017, Tiepelt 2017).

5.5.2 Farmers

Tiepelt (2017) regards farmers as another major potential participant/client, especially dairy farmers and housed dairy farmers. In terms of financing a project on this scale, there are two major primary requirements. The first major requirement is a signed agreement for feedstock, and secondly, a signed agreement for energy off-take. GreenCape (2016) supports this by listing availability of sufficient feedstock and the lack of feed-in tariffs for renewable energy outside of the REIPPPP, which only applies to projects larger than 5 MW as a challenge. GreenCape (2016) also states that the biggest opportunity for biogas production in South Africa is in the accumulated benefits of multiple small-scale plants on farms but that farmers are often negatively affected by the challenges of the industry such as perceived financial losses and skills shortages (GreenCape 2017a, GreenCape 2017c).

Enablers:

- Better negotiation of contract agreements, especially taking into account that biogas facilities differ dramatically from farm to farm and are influenced by the merits of each situation (GreenCape 2017a).
- Ensuring consistent feedstock supply and consistent off-take will enable more efficient and cost-effective operations (GreenCape 2017a).
- Increased trust in developers and the validity of their products as well as better product warranties could increase interest in new technologies (GreenCape 2017a, GreenCape 2017c, Steyn 2017).
- GreenCape (2017a) has established an agriculture portal managed by their agriculture desk to inform the farming community about sustainable agriculture practices such as biogas generation.

5.6 Skills shortage and development

A particular hindrance in South Africa is the major skills gap due to the lack of available and qualified biogas skills development avenues and restricted access to biogas specific education, both locally and internationally (SAGEN and SABIA 2016, GreenCape 2017c). Mutungwazi *et al.* (2017) found that the failure of biogas digesters could be ascribed to the suitability and availability of the materials used, poor building skills and lack of knowledge regarding system design and operation. Tiepelt (2017) confirmed that South Africa lacks the experience of operating biogas plants that is needed to optimise the country's biogas potential. GreenCape (2017c) stated that insufficient knowledge and skills training has resulted in several costly process issues. With developers currently being the only party investing in mostly in-house skills training, there exists little potential for cross-pollination of skills from outside of the industry. SAGEN and SABIA (2016) predicts that this skills gap will expand with the growing market should there be no intervention and standardisation of technical skills.

***Enablers**:*

- Creating opportunities to train skilled or semi-skilled employees in the biogas sector, may resolve in cheaper labour cost for better and consistent qualified labour (SAGEN and SABIA 2016, Tiepelt 2017).
- The South African Renewable Energy Technology Centre (SARETEC) is the first national renewable energy technology centre of its kind in the country, located at the Cape Peninsula University of Technology (CPUT). SARETEC promotes specific industry-related and accredited training for the renewable energy industry including short courses and workshops (SARETEC 2017). GreenCape (2017a) believes that SARETEC could assist in skill training.

5.7 Ethical challenges

The use of sewage sludge as a soil conditioner presents a psychological and ethical challenge. Walekhwa *et al.* (2009) described this as a socio-economic factor that can influence the uptake of biogas digesters projects. Possible negative impacts on the development of the industry are the potential for pathogens present in the digester slurry to contaminate the people who handle it or eat crops fertilized with it (DA, DH, DAFF, WISA and WRC 1997, Brown 2006, Yongabi *et al.* 2009). Rabezandrina (1990) and Amigun and Von Blottnitz (2009) also noted as hindrances the potential to pollute water souces through leakages from faulty digesters or from runoff of undigested material that has been applied to soils. However, this is contradicted by studies that maintain that biogas destroys pathogens through the thermophilic AD, meeting the requirements of the hygienic indicators of the European Union (Paavola and Rintala 2008).

Enablers:

- Using the digestate as a soil enhancer and for soil preparation presents no problems when the digestate does not come into direct contact with the edible parts of the produce (Paavola and Rintala 2008). In the past in South Africa, farmers have used the sludge of wastewater treatment works as a source of soil conditioner/enhancer in soil preparation (DA, DH, DAFF, WISA and WRC 1997). Tiepelt (2017) further confirms that sewage sludge is still being used in this sense in South Africa, showing a change in acceptance of alternative sources of fertilisers (Tiepelt 2017).

5.8 Water resources

South Africa is a water-scarce country (OXFAM 2016). This presents challenges for the biogas digester industry and especially for smaller scale digesters as anaerobic digesters require a lot of water to function (Swanepoel 2014).

Enablers:

- Tiepelt (2017) believes that this should not restrict the growth of the industry as large volumes of the liquid digestate can be recirculated and used for further dilution. While this cannot be done indefinitely; up to 80 % of the liquid can be reused depending of the type of feedstock, reducing the water requirements of a digester substantially (Morales-Polo and del Mar Cledera-Castro 2016, Bansalet *et al.* 2017).
- Reutilising the liquid digestate also has its benefits as the temperature of reused digestate is higher and the warmer water creates a more suitable micro habitat for digestion (Morales-Polo and del Mar Cledera-Castro 2016, Bansalet *et al.* 2017, Tiepelt 2017).

5.9 Access to and segregation of waste

As many thermal waste-to-energy technologies need large-scale facilities to be viable and achieve economy of scale (e.g. 1 000-2 000 T/day), access to sufficient feedstocks can be a challenge (GreenCape 2016, GreenCape 2017a, GreenCape 2017c). Low gate fees at landfill sites also make it difficult for other technologies to compete with landfilling as the cheaper alternative (GreenCape 2016, GreenCape 2017b). Current waste laws (NEM:WA) prevents abattoir waste to be treated with municipal wastewater or sent to landfills which enable the use of anaerobic digestion to dispose abattoir waste.

Transparencymarketresearch (2017) states the overall lack of effort going into the separation of wastes before disposal as a global hindrance that can negatively affect developing countries. There is a major absence of implementation of processes meant to sort waste, which is the basic requirement for any waste type to be reused or recycled. While the global biogas plant market is in a very good position to increase its output volumes and infrastructure, it is particularly held up by this lack of waste segregation policies and systems, especially in emerging economies around the world.

Interventions with the aim to divert 100 % of organic waste from landfills may result in less organic waste being available for biogas generation (GreenCape 2017a). A challenge faced in fertiliser production is the inconsistent control of minerals included in the digestate as the composition of digestate differs as feedstock types differ. This is especially true regarding municipal solid waste as the feedstock often consists of random portions of waste resulting in inconsistent output. The unintentional inclusion of foreign objects or toxic substances in waste could lead to health issues or financial losses (GreenCape 2017b, GreenCape 2017c).

In addition, competition for wet food waste is very high between pig farmers, fly farmers, compost companies and biogas producers, especially waste solutions that may be more financially feasible (GreenCape 2017a).

Enablers:

- Stricter licencing requirements for the diversion of organic waste from landfills could mean that alternative solutions for organic waste such as biogas generation are explored (GreenCape 2017a).
- Biogas generation creates waste disposal solutions for companies reducing waste transport costs and the costs of generation heat and electricity (GreenCape 2017a).
- Streamlining biogas generation legislation could act as an enabler in this regard (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017).

Results and discussion

Biogas generation has a long history in South Africa, with its initial application limited to treat sludge in wastewater plants. The growing interest in biogas generation in recent years can be attributed to its potential to provide solutions for the continued challenges faced in terms of energy generation and waste management (GreenCape 2017a, GreenCape 2017c, Tiepelt 2017).

Biogas generation could potentially contribute to the alleviation of poverty and the improvement of the well-being of communities, by integrating waste management and renewable energy technologies (Biogas 2013, DEA 2013, SAGEN and SABIA 2016, GreenCape 2017a). In this way it presents a unique opportunity to impact all three pillars of sustainability in a developing country like South Africa.

Biogas generation as an alternative renewable source of energy could potentially mitigate the effects of climate change and enable the country to meet peak electricity demands as it is not dependant on resources like wind or water and can be implemented on any site where waste feedstock is readily available. This also makes it a suitable option for small or farm-scale application as rural wastes are mostly organic and biogas energy generation can provide options to save on electricity bills and provide innovative solutions to waste management problems (SAGEN and SABIA 2016) while the digestate has the potential to be repurposed as organic fertiliser. In addition numerous ecosystem services are rendered that could ultimately increase food production (NERSA 2013, Ji-Quin and Nyns 1996), again linking the benefits of biogas generation to the Sustainable Development Goals of the United Nations (UNDP 2017).

While South Africa's sustainable development policies commit the country to a sustainable development path (DEA 2008, DEA 2013, DEA 2016) the slow development of anaerobic digestion, both on a commercial and rural scale, as compared to other developed and developing countries, could be due to numerous challenges such a lack of awareness of the industry, a lack of government support, intensive capital investment requirements, slow and hindering legal processes, a skills shortage, ethical challenges and the complicated nature of electricity supply and demand.

Enablers could however contribute to the growth of the industry and include skills training, increased trust and safeguards in the products installed, streamlining of legislation pertaining to licencing, carbon incentives and waste, and joint ventures between the public and private sector to alleviate financial constraints. Exemption from electricity licences, the proposed SSEG tariffs and new frameworks for wheeling arrangements will increase the opportunities to feed excess electricity into the grid or sell it to clients directly (GreenCape 2017a, Scharfy *et al.* 2017).

What counts in favour of the development of this industry is the perceived tenacity of project developers that continue to pursue the development and marketing of such systems even in a situation where there is limited awareness and knowledge about biogas generation (Tiepelt 2017). They are supported in their endeavours by the contribution of the South African Biogas Association and various industry stakeholders such as GreenCape.

Conclusion

With the acknowledgement of the critical importance of moving towards more sustainable development in South Africa, and taking into account South Africa's vision for sustainability, the use of anaerobic digestion for the generation of electricity and efficient waste management has great potential to contribute significantly to sustainable development. This is measured against the growth in the biogas generation industry seen over the last decade, even in the face of numerous challenges such a skill shortages, lack of financial incentives, financial constraints, ethical issues, limited water resources and policy and legal requirements.

Biogas generation has the potential to contribute to a more sustainable farming approach through the production of energy and thermal heat to be used on site, reduction in electricity costs, providing waste management solutions and the production of organic fertiliser for own use or as an additional source of income.

In the rural sector the generation of electricity and gas could not only contribute to local economic development but also to the quality of the lives of people through the use of an alternative energy source to enhance the quality of their lives.

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PAPER 2: EVALUATING THE POTENTIAL OF ON-FARM BIOGAS GENERATION AS A SUSTAINABLE AGRICULTURAL PRACTICE THROUGH INTER-ACTION WITH THE FARMING COMMUNITY

Abstract

The rationale of this study was to establish the potential of farm-scale biogas generation as a sustainable agricultural practice in South Africa. Findings are based on interaction with two groups of farmers – 1) those without biogas digesters and 2) those with biogas digesters. Purposive data collection was conducted through two self-administered electronic surveys that were sent to farmers of both these groups. Farmers in the Western Cape, KwaZulu-Natal, Mpumalanga, Northern Cape, Free State and Gauteng were included in the surveys, covering agricultural practices such as animal husbandry, agronomic crops, fruit and aquaculture. Information obtained was further supported and clarified through personal conversations with participants in both surveys and measured against what is defined in this paper as sustainability, economic potential, social potential and environmental potential – the three so-called pillars of sustainability. It was found that, although substantial understanding of sustainability, effects of climatic change and the economic potential of biogas generation exists, a lack of knowledge, expertise, financial support and incentives remains an obstacle in the practical implementation of biogas generation and the potential it shows to provide a cost-effective renewable source of energy to enhance the quality of life in rural areas.

1.0 Introduction

1.1. Biogas production as a sustainable agricultural practice

Sustainability is an important concept in this study, as the potential to generate biogas as a sustainable agricultural practice is evaluated against the impact it may have on the three pillars of sustainability namely economic, social and environmental.

In this paper sustainability is defined as: "*The process of utilising and living within the limits of available physical, natural and social resources in ways that promote social, ecological and economic sustainability all at the same time, while allowing the living systems in which* *humans are entrenched to flourish in perpetuity*" (UN 1987, DEA 2008, Kuhlman and Farrington 2010, Morelli 2011, EPI 2014, Uwosh.edu 2017).

The agriculture sector in South Africa shows great sustainable potential for biogas implementation on small to medium farm scale (Smith 2011, Biogas 2013, Hamilton 2014, Shah *et al.* 2015, Zafar 2015, GreenCape 2016, GreenCape 2017a, Tiepelt 2017).

South Africa was one of the first countries in the world to utilise biogas on a pig farm south of Johannesburg in the early 1950s (GIZ-SALGA 2015), with the two biggest participants in biogas generation today being identified as municipalities and farmers – especially dairy farmers and housed dairy farmers (GreenCape 2016, GreenCape 2017a, Tiepelt 2017).

Not only could farm-scale biogas generation stimulate the much-desired rural renewal, improve long-term sustainability of ecosystem services and address energy poverty in South Africa; the biggest opportunity for biogas production lies in the accumulated benefits like many decentralised small-scale plants on farms (Mshandete and Parawira 2009, Smith 2011, Amigun *et al.* 2012, NERSA 2013, GreenCape 2016). Farms could benefit through the generation of electricity, waste treatment, storage and transportation and fertiliser production, especially as energy has been identified as a major element in the competitiveness and sustainability of the farming sector (Mshandete and Parawira 2009, Smith 2011, Abbasi 2012, Biogas 2013, Griffiths 2013, NERSA 2013, Carter and Gulati 2014, SAGEN and SABIA 2016, GreenCape 2017a, Tiepelt 2017). Lutge (2010) found that as far as the economic potential of on-farm electricity generation through biogas is concerned, each farm should be treated as an independent unit. This supports the notion to direct surveys to individual farmers, those who do not make use of biodigestion, as well as those who do, in an effort to establish whether any common denominators exist that could influence their decisions.

Previous studies analysed the biogas potential of wastewater treatment plants (GIZGmbH 2016) and the potential for domestic biogas as household energy supply (Msibi and Kornelius 2017), as well as the potential of producing biofuels as a new technology to overcome food security and resource issues (Amigun *et al.* 2011). Kumba *et al.* (2017) investigated the design and sustainability of a biogas plant for domestic use. No surveys directed to individual farmers to assess the on-site agricultural potential of biogas generation have been known to be published so far. Msibi and Kornelius (2017) found that based on livestock numbers, some 625 000 South African households could benefit from biogas generation based on cattle and pig waste, but that it is not feasible to run a domestic bio-digester on only human, chicken and food waste because of inadequate feedstock. Amigun *et al.* (2011) concluded that biofuels, in themselves, pose few sustainability risks for food production in terms of land and water resources and that its conservative application could enhance the productivity of the agricultural system. Kumba *et al.* (2017) studied design parameters for biogas digesters through field surveys and concluded that the organic loading rate, hydraulic retention time and feedstock play a major role in determining the design of such systems.

The willingness or non-willingness of participants, and those who were approached to participate in this study, gave further insight into the potential of biogas generation in the agricultural sector as it highlighted the limitations set on the industry through perceptions and frustrations experienced. The scepticism encountered is supported by Amigun *et al*. (2011) who have pointed out that some small-scale farmers are sceptical of new ventures and generally are not willing to engage in farming activities that they are not familiar with.

The study expects to gain insight into the understanding, knowledge, experience and awareness of sustainability, climate change and implementation of biogas digesters on farm scale, as well as to identify major challenges faced by these farmers, hindering the process of unlocking of the sustainable potential of biogas generation on farm scale in South Africa.

1.1.1 The economic potential of biogas production as a sustainable agricultural practice

Energy is a driver of economic growth and it is estimated that biogas generation could supply about 6 % of the global primary energy demand, or one quarter of the present consumption of natural gas (Holm-Nielsen *et al.* 2007, World Economic Forum 2012). Energy is also regarded a major element in the competitiveness and sustainability of the farming sector, and that is why anaerobic digestion is seen to have the highest potential to be implemented on farms that as a potential solution to South Africa's ever-present electricity crisis, and the resultant trends of unsustainable consumption and production (Smith 2011, Amigun *et al.* 2012, Griffiths 2013, Carter and Gulati 2014, SAAEA 2016, SAGEN and SABIA 2016, Teljeur *et al.* 2016, Tiepelt 2017).

For the purpose of this paper, economic potential is defined as *"the available technical potential in terms of biogas generation, where the cost required to generate the energy (which determines the minimum revenue requirements for development of the resource) is* *below the revenue available in terms of displaced energy and displaced capacity"* (Brown *et al.* 2016).

It is maintained that economic potential can be realised in the agricultural sector for the following reasons:

1.1.1.1 The potential to supply in energy/heat demands by making use of the availability of feedstock

Anaerobic digestion (AD) produces biogas when organic matter, such as plant material, animals and their wastes and waste water, decay through a natural anaerobic bacterial process, offering the possibility to regionalise energy delivery (Dennis and Burke 2001, Arbon 2005, Amigun *et al.* 2012, Biogas 2013, Shah *et al. 2*014, GreenCape 2017a). GreenCape 2016 estimated that the total electricity potentially generated from biogas in South Africa from agricultural waste is 2 300 MWe (MegaWatt electric), and Abbasi (2012) predicted that by 2020 the largest volume of produced biogas will come from farms and large co-digestion biogas plants that are incorporated into farming and food-processing structures.

1.1.1.2 The potential to produce organic fertiliser that can be used as soil conditioners or compost

There is sufficient scientific and practical evidence of the capability of digestate to act as a soil conditioner and to enhance plant growth and yields, especially taking into account that nearly 80 % of South African land is agricultural land with an estimated fertliser use of 60,6 kilograms per hectare of arable land (Dennis and Burke 2001, Tambone *et al.* 2007, Schleiss and Barth 2008, Tambone *et al.* 2009, Dillon 2011, Makádi *et al.* 2012, Torquati *et al*. 2014, Msibi 2015, SAGEN and SABIA 2016, Culhane 2017, GreenCape 2017a, Tiepelt 2017, Tradingeconomics.com 2017). Biogas generation on farm scale could provide a mechanism to reuse waste for soil conditioning and to save on fertiliser costs, as the digestate could be used as a treated soil conditioner on site or supplied to agricultural fertiliser producers (GreenCape 2016, Tiepelt 2017).

1.1.1.3 The potential to find affordable financial solutions to the challenges of operational costs and revenue possibilities

Substantial capital costs make the return on investment into a biogas plant for a farmer that has access to a reasonable amount of organic waste, directly dependent on the replacement cost of Eskom-bought electricity (BiogasSA 2017). However, long payback periods, limited electricity generation potential and the lack of feed-in tariffs for renewable energy outside of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), makes it a risky and unattractive investment for the average farmer in South Africa (GreenCape 2017c, BiogasSA 2017). Numerous incentives are however underway that could make biogas generation on farm-scale more viable including better negotiation of contract agreements, especially considering the merits of each situation; ensuring consistent feedstock supply and consistent off-take; using both heat and electricity generated on site; and selling electricity generated at a premium through newly-negotiated power purchase and wheeling agreements with municipalities (GreenCape 2017a).

1.1.1.4 The potential of accessing realistically available governmental support

Incentives and rebates could make farm-scale biogas plants a lucrative option for farmers looking to reduce their carbon footprint and save on electricity bills (Biogas 2013, Griffiths 2013). However, the effective implementation and allocation of funds regarding these incentives are found to hinder the potential of biogas generation development in South Africa (AltGen, GIZ, SAGEN and GreenCape 2014, DTI 2015, Creamer 2016, ESI-AFRICA 2016, GreenCape 2016, Tiepelt 2017). Future enabling factors could include exemption from electricity generation licences; the potential to sell electricity to a third party through power purchase agreements; the fact that municipalities could possibly buy electricity from any independent power producer and not only from Eskom; and creating a market for surplus energy generated by plant with a capacity of <1MW (AltGen, GIZ, SAGEN and GreenCape 2014, SAGEN and SABIA 2016, Tiepelt 2017). It could also provide tax relief through the anticipated implementation of carbon tax; promote solutions for waste management and the organic fertiliser industry, while delivering ecosystem services such as carbon sequestration in soils and improved water and soil quality and, ultimately, an increase in food production (Onwosi and Okereke 2009, Mtambanengwe and Mapfumo 2005, Fonte *et al.* 2009).

1.1.2 The social potential of biogas production as a sustainable agricultural practice

As agricultural activities directly affect the social life and well-being of communities, it can be seen as maintaining social viability in rural communities (OECD 2000). In the same way, biogas generation is linked to the Millennium Development Goals of reducing income poverty, promoting gender quality, promoting health and environmental sustainability (UN 2015). Farm-scale biogas digesters have great potential to contribute to sustainable development by providing a secure energy supply, enhanced regional and rural development and employment opportunities, and the creation of a domestic industry (Rio and Burguillo 2008, Mshandete and Parawira 2009, NERSA 2013).

For the purpose of this paper, social potential refers to "*Identifying and evaluating the social issues and related indicators that can enhance social conditions in South Africa related to sustainable development of biogas generating facilities*".

It is maintained that social potential can be realised in the agricultural sector for the following reasons:

1.1.2.1 The potential to create jobs and opportunities for skills transfer and education

Probably the most important consideration when promoting the South Africa biogas industry is its potential to generate five times more permanent job opportunities than solar energy (Ruffini 2014, SAGEN and SABIA 2016). As a lack of skills for the operation and functioning of a biogas plant on farm-scale is seen as a challenge (Tiepelt 2017), initiatives such as the agricultural portal on sustainable agriculture at GreenCape that creates training opportunities to skilled or semi-skilled employees through The South African Renewable Energy Technology Centre (SARETEC), opens the opportunity to build knowledge, skills and experience (GreenCape 2017a) especially in the agricultural sector.

1.1.2.2 The potential to deliver health benefits and improve the standard of living

It is estimated that half a billion people in sub-Saharan Africa rely on solid biomass, such as wood, animal waste and agricultural residues, to meet their basic energy needs and that solid biomass accounts for nearly 74 % of total energy use (Brown 2006, Mshandete and Parawira 2009, Amigun *et al.* 2012, Msibi 2015). This creates substantial potential for biogas generation to provide health and environmental benefits, especially in rural (farming) communities where poverty levels are high, where a cheaper alternative to electricity is sought, and where sufficient organic waste is available as feedstock (Amigun and Von Blottnitz 2010, Smith 2011, Amigun *et al.* 2012, Biogas 2013, Msibi 2015, GreenCape 2016, SAGEN and SABIA 2016, GreenCape 2017a, Msibi and Kornelius 2017).

1.1.2.3 The potential of increasing the footprint of biogas generation in rural areas with government support

There are several developers and governmental programmes working to implement biogas projects within the rural sector supporting the notion by making energy more accessible and affordable to disenfranchised communities, the health and well-being of communities will change for the better. The South African National Energy Development Institute (SANEDI) is currently responsible for managing and rolling out the Working for Energy Programme, a renewable energy initiative focused on providing thermal energy and improving the quality of life for people in rural communities. They are involved in three initiatives totalling about 190 active digesters, which include the Melani Village Biogas Expansion Project, the Illembe District and Mpufuneko Biogas Projects (SAGEN and SABIA 2016). The project is an ongoing and funded by the Department of Energy (DoE) through their subsidiary, SANEDI (UFH 2017). The formation of the Southern Africa Biogas Industry Association (SABIA) underscores the anticipation of the growth of the biogas industry in South Africa (ESI-AFRICA 2016).

1.1.3 The environmental potential of biogas production as a sustainable agricultural practice

In response to growing stress on environmental systems and natural resources, the National Framework for Sustainable Development (NFSD) commits South Africa to a long-term programme of resource and impact decoupling and outlines principles and trends regarding sustainability, as well as a set of implementation actions (DEA 2013). The Department of Environmental Affairs (DEA 2017) states that is imperative that the energy mix should take into account its potential environmental impact and should address sustainability by amongst others mitigating the effects of climate change.

For the purpose of this paper, environmental potential is defined as "*the environmental capacity of structures, processes and functions of ecosystems, bringing together natural* *physical, chemical, physiographic, geographic and climatic factors, and further integrating these conditions with anthropogenic impacts and activities of concern, to ensure procurement of environmental sustainability*".

It is maintained that environmental potential can be realised in the agricultural sector for the following reasons:

1.1.3.1 The potential to contribute to the reduction in greenhouse gas emissions

The South African government has committed to a 34 % reduction in greenhouse gas emissions by 2020 (Teljeur *et al.* 2016), and GreenCape (2017a) believes that farm-scale biogas generation could save on carbon emissions especially when used as an alternative fuel. Torquati *et al.* (2014) regards the contribution it can make to reduce CH_4 emissions from the natural decay of organic matter, and in the overall decrease in CO_2 emissions that can be brought about by the use of alternative energy sources as significant. ESI-AFRICA (2016) states that local biogas production is further stimulated by the prevailing biogas feed-in tariff and recent environmental legislation which encourages the establishment of biogas plants, i.e. the National Environmental Management Act (NEMA), the National Environmental Management: Waste Act (NEM:WA), the National Environmental Management: Air Quality Act, the National Waste Management Strategy (NWMS) and the Income Tax Act Amendment 12L (Cleaner Development Mechanism).

1.1.3.2 The potential to supply renewable energy

South Africa also has a very specific electricity load profile that does not necessarily match the period of highest solar energy generation, nor does wind energy profiles fit in predictably with this demand profile (Griffiths 2013). This leaves a gap for biogas electricity generation to alleviate peak hour demand. As long as the plant is maintained and correctly supplied with feedstock, generation from biogas is not dependent on any external conditions, making it very suitable for agricultural use (Griffiths 2013, GreenCape 2017a). Tiepelt (2017) regards the farming community as the ideal take-off as it can make use of the energy as well as the heat that is generated.

1.1.3.3 The potential to contribute to soil health and increased food production

Ecosystem services that are potentially delivered through the application of organic matter (OM) are increased carbon (C) sequestration in soils, improved water quality, decrease of local pollutants and improvement in water quality, reduced erosion, better soil structure and water holding capacity and ultimately an increase food production (Ji-Quin and Nyns 1996, De Neve *et al.* 2003, Mtambanengwe and Mapfumo 2005, Lantz *et al*. 2007, Mwakaje 2008, Fonte *et al.* 2009, Onwosi and Okereke 2009, Yongabi *et al.* 2009, NERSA 2013). Among the varied available organic wastes, biogas residue was found to be more efficient for promoting the soil microbiological activity, and substrate-induced respiration increased with the high amount of easy-degradable carbon that resulted from higher plant growth (Makádi *et al.* 2012). As the use of anaerobic digestion is known to destroy pathogens, using manure as feedstock on site could potentially reduce the spread of unwanted pathogens and detrimental nitrate accrual in the water table (Paavola and Rintala 2008, SAGEN and SABIA 2016).

2. Materials and methods

Two self-administered electronic surveys (Babbie and Mouton 2001) were constructed: (S1) *Farmers without biogas digesters*, and (S2) *Farmers with biogas digesters*. The S1 survey (APPENDIX C) was sent to 25 farmers and responses were received from 10 participants. The S2 survey (APPENDIX D) was sent to nine farmers, and responses were received from five. The purposive sample size for S2 (farmers with biogas digesters) is small, as it was found to be extremely difficult to locate farmers who have installed on-farm digesters for their own use. The details of all of the participants are summarised in Table 1.

For S1, the study identified farmers not only with high quantities of suitable feedstock types, but with a variety of feedstock types in different areas of the country. For S2, the study only focused on farmers who have installed, operated and maintained biogas generators at their own cost; and not on biogas digesters which have been installed on farms on a commercial scale or that are installed, operated and maintained at the cost of the developer or in a joint venture with a developer.

Table 1: Details of farms without biogas digesters (S1), and farms with biogas digesters (S2) as incorporated into this study.

Farmers without biogas digesters (S1)		
Name	**Location**	**Type**
Mhlati sugar	Pongola, KZN	Cultivate sugarcane, export citrus/mangos/pecan & macadamia nuts
Waterkloof	Williston, NC	Sheep farming
Albertina	Koppies district, FS	Cattle, sheep, crops (maize, sunflower, soy beans)
De Vlei	De Doorns, WC	Table grape production
Mariendahl	Stellenbosch, WC	Cattle, sheep, pig farming
Goedgeleë	Overberg district, WC	Grain, dairy, wool sheep
Doornfontein	Malmesbury, WC	Dairy, wine grape, roll on lawn, sheep
Elandsfontein	Britstown, NC	Organic sheep farming, livestock and crop production
Kendal poultry farm/Fair Acres	Lanseria, MP	Egg production
Lazena Farm and various contract farms	Gordon's Bay, WC	Broiler chickens and abattoir

Farmers with biogas digesters (S2)			
Name	**Location**	**Type**	**Year (installer)**
Riverside Piggeries	Pretoria, Gauteng	Piggery	2015 (ACRONA SA)
No2Piggeries	Queenstown, KZN	Piggery and dairy	2014 (iBert)
Swineline	Cullinan, Gauteng	Piggery	2012 (Self-installed)
Uilenkraal	Darling, WC	Dairy and animal feed factory	2013 (CAE)
Welgevallen Experimental Farm	Stellenbosch, WC	Semi-commercial dairy, fruit, vines, sheep and aquaculture	2015 (Sustainable engineering consultants and self-installed)

The reasoning was to focus on the benefits and challenges facing farmers alone, and not to cloud the investigations with issues affecting developers. This study also made use of SABIA (South African Biogas Industry Association), SELECTRA, biogas development/instalment companies such as BiogasSA, AGAMA BiogasPro and iBert, as well as other experts in the field to locate the farmers with biogas digesters. Each participant was initially contacted by telephone and surveys were sent and received via email. This was in many cases followed up by in-depth telephone conversations.

3.0 Results

3.1. Comparative analyses of awareness and understanding of sustainability between both farmers without biogas digesters (S1) and farmers with biogas digesters (S2)

All of the participants stated that they are aware of the term sustainability, but 20 % of both S1 and S2 participants could not distinguish between the terms organic and sustainability. 80 % of participants for both surveys could complete the definition of sustainability stating that "*sustainability is the process of utilizing and living within the limits of available physical, natural and social resources in ways that promote social, ecological and economic sustainability*", while one participant in S1 stated that the process of sustainability only promotes ecological sustainability, and another participant in S2 stating that it only promotes social and economic sustainability. All of the participants in both surveys (S1 and S2) felt that farmers should incorporate more sustainable practices in South Africa. The 90 % (S1) and 100 % (S2) were of the opinion that this is what consumer's demand, while one participant (S1) thought that there is only a consumers' demand in certain niches. All of the S1 participants were of the impression that it is not too late for farmers to incorporate more sustainable practices into their farming approach.

70 % of S1 participants replied that the electricity crisis in South Africa affects agricultural practices which results in financial losses. All S2 participants agreed with this statement, whereas 100 % of both S1 and S2 participants believes that generating environmentally friendly electricity would promote sustainability for the country.

Farmers with biogas digesters (S2) were slightly more optimistic regarding sustainable agricultural practices and the role of biogas generation in sustainable development, with 40 % stating that they are living in a sustainable manner and 60 %, that they are not yet living in a sustainable manner, but that they are trying to achieve it. On the other hand, only 20 % of farmers without biogas digesters (S1) lived in a sustainable manner, with 40 % not doing so, but trying to achieve this (Figure 1).

The majority (80 %) of S2 participants agreed that the implementation of a biogas digester contributes towards sustainability. One participant disagreed, but it was established that this particular participant's understanding of sustainability was misconceived.

Figure 1: Efforts by S1 (farmers without biogas digesters) and S2 (farmers with biogas digesters) towards living in a sustainable manner.

3.2. Comparative analyses of awareness and understanding of climatic changes between both farmers without biogas digesters (S1) and farmers with biogas digesters (S2)

The level of awareness and understanding of climate change by both S1 and S2 participants were extremely high. All S2 participants indicate that they have an understanding and knowledge of climatic changes and GHG emissions. All S1 participants stated that they are aware of climatic changes; 80 % are aware that methane (CH_4) and carbon dioxide (CO_2) are some of the biggest contributors towards climate change and 90 % stated that they are aware that agricultural activities produce methane and carbon dioxide in large uncontrolled quantities. 90 % of S1 participants stated that changing climatic conditions have an negative effect on their agricultural practices, referring to season changes i.e. lower annual rainfall, water availability, extreme droughts, acid rain and temperature fluctuations, where all of these negatively affect the economic viability of their farming practices (i.e. higher maize prices due to lower rainfall, lower milk production due to higher temperatures, poultry mortalities, lower immunity of livestock against diseases, change in shifting crop cycles and production, often resulting in smaller crops and lower production).

One of the S1 participants noted that these known effects of climatic change has adjusted the mind-set of some farmers towards taking social responsibility of GHG emissions and climate change.

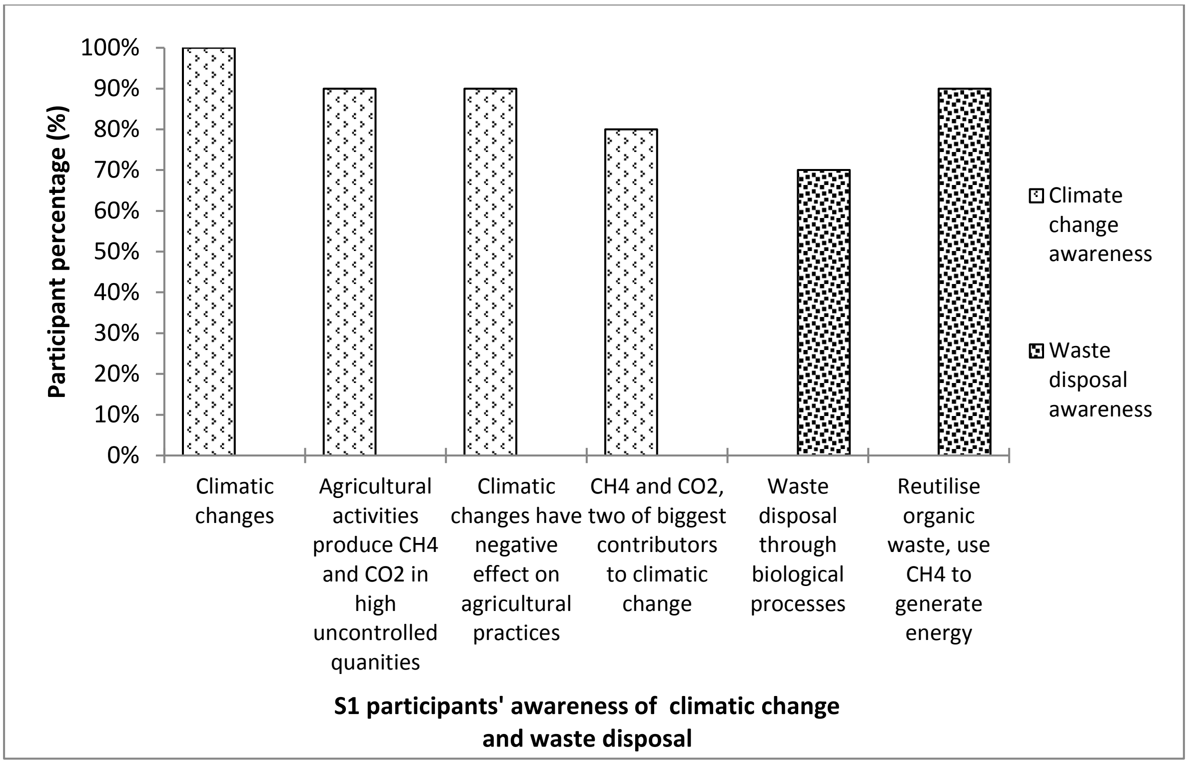

Figure 2: The level of S1 participants' awareness of climatic change contributors, and effects on agricultural practices for farmers without biogas digesters.

3.3 Results for S1 participants – farmers without biogas digesters

3.3.1 Biogas generation awareness, waste management, fertiliser usage and electricity demand and supply

3.3.1.1 Participant awareness of biogas digester technology

The majority of the S1 participants (80 %) are aware of biogas digester technology; the 20 % who indicated that they are unaware of a biogas digester are livestock farmers located in the Northern Cape Province and Free State Province of South Africa. All S1 participants were able to identify that biogas generation is the natural anaerobic decomposition of organic material to collect carbon dioxide (CO_2) and methane (CH_4), and to use the methane to generate energy in the form of gas or electricity.

3.3.1.2 Waste disposal management

S1 participants identified the following waste streams applicable to their farming practices: animal manure (70 % of the participants), organic plant matter (40 % of the participants), animal body parts (40 % of the participants), plastics (30 % of the participants) and waste water (30 % of the participants). Participants could choose more than one waste stream.

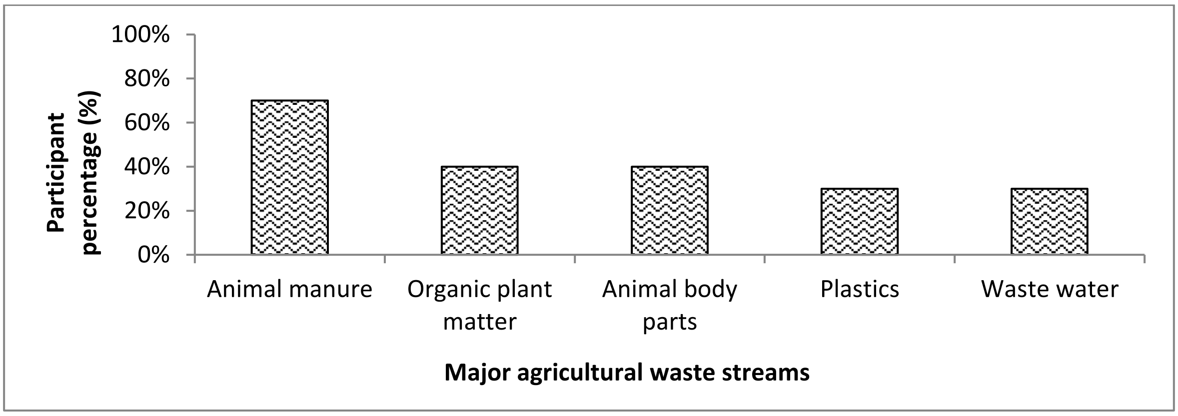

Figure 3: Major agricultural waste streams applicable to S1 participants.

Participants indicated that these agricultural waste streams on their sites are currently managed and disposed through the following methods (Figure 4): burning (30 %), transport to landfill site (30 %), crop waste recycled for feed (cattle and sheep) (10 %), organic plant matter reused as soil amendment (20 %), animal manure worked into soil/spread on crops and plantations as soil amendment to increase soil organic matter (60 %). Household waste (plastic bags, cans and cardboard) is delivered to municipal solid waste facilities where it is recycled (40 %). Where free range is practiced – no animal waste (10 %) was reported. Participants could choose more than one method to manage waste streams.

70 % of participants are aware of biological means to get rid of agricultural waste, with 90 % confirming that they are aware that animal waste, organic plant matter and abattoir waste can be used to generate methane for cooking, heating and to generate electricity (Figure 2).

The cost associated with waste disposal varied significantly per participant, on all levels of agricultural practice. 60 % of participants had zero costs associated with waste disposal, for 30 % costs ranged between R1 000 to R5 000 per month, with one outlier noted of R200 000 per month.

The majority of participants that did incur waste disposal costs noted that waste was routinely repurposed to save on these costs and showed innovation in using aerobic decomposition to repurpose their waste:

- pig manure is washed off in water-driven channels and flushed into cement tanks, stirred and pumped over sieves to separate liquid and solids, the liquid ferments in holding dams and gravitates into a larger rainwater dam from where irrigation takes place; dairy waste water is also directed to a holding dam from where it is applied as a liquid fertiliser during irrigation,

- solids are spread on pastures in lieu of fertiliser,
- bedding (straw and cattle or sheep manure of cattle and sheep) are left to rot during winter months and/or
- dead animals are buried in trenches.
-

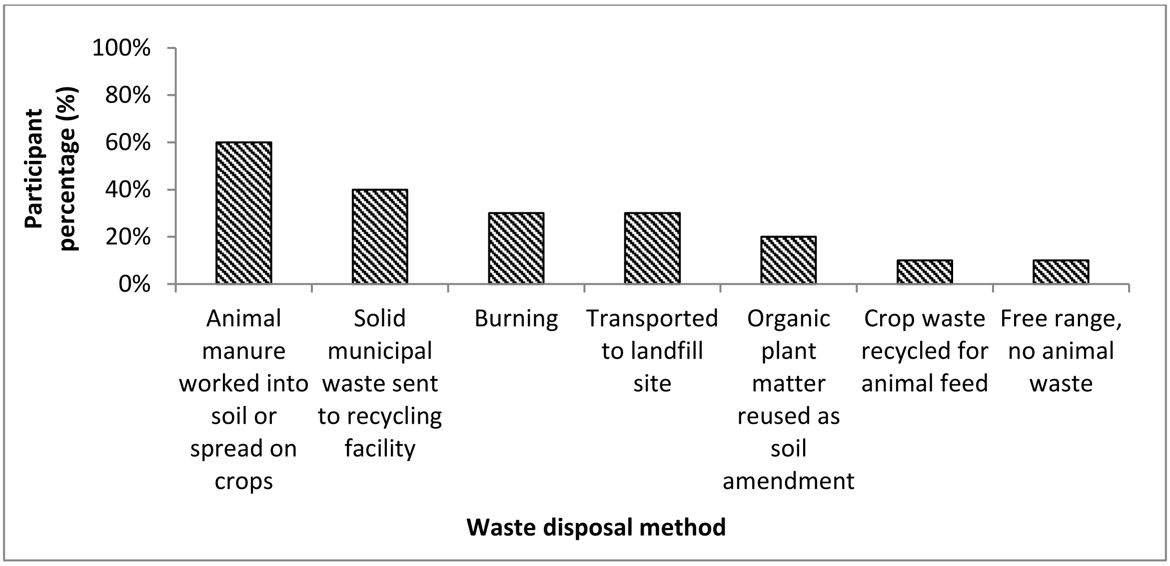

Figure 4: An illustration of methods used by S1 participants to dispose of their agricultural waste.

3.3.1.3 Fertiliser usage

While 60 % of participants indicated that they use raw forms of manure or sludge as soil amendment for soil preparation, 70 % stated that fertiliser remains a major farming expense. No participants used raw sewage from waste water treatment works as soil conditioner for soil preparation.

3.3.1.4 Electricity demand

90 % of the S1 participants do not generate their own electricity, with only one participant admitting to partly making use of solar power generation. Participants indicated the absence of known governmental incentives or rebates for the generation of environmentally friendly (green) electricity as a reason for not generating their own electricity.

All participants are connected to the Eskom grid for electricity supply, of which 80 % stated that electricity is a major expense on the farm. 60 % of participants admitted to experiencing power cuts that influence their agricultural practices, ultimately leading to financial losses; 30 % experience power cuts that influence their agricultural practices, without any financial losses, and only 10 % of participants indicated that they do not experience power cuts.

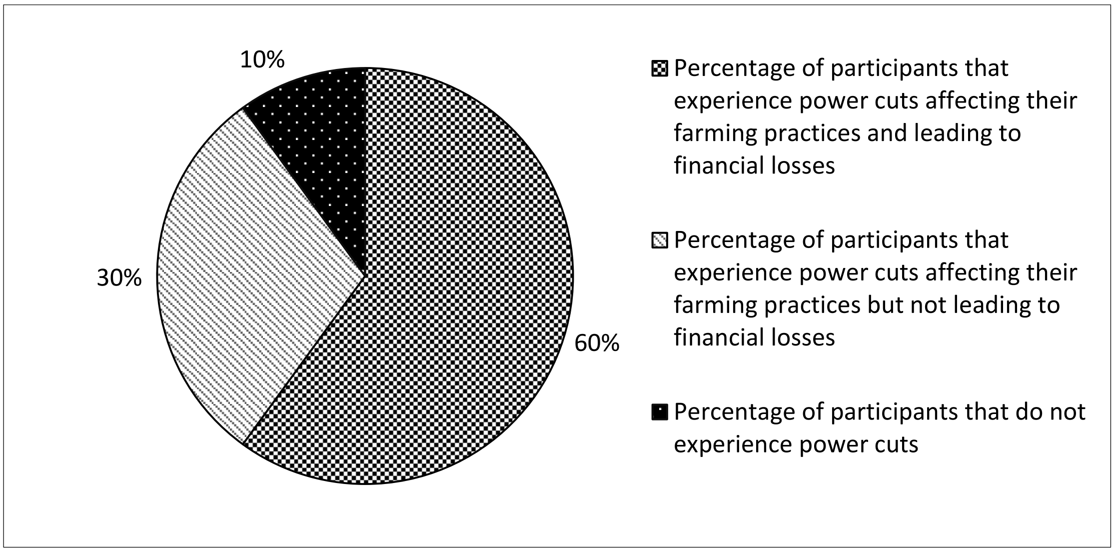

Figure 5: Illustrating the degree to which S1 participants are affected by power cuts

S1 participants indicated the following energy sources in use on their farms: electricity, gas and fuel wood (40 %); electricity and fuel wood only (20 %); electricity only (20 %); electricity and gas only (20 %). It was also indicated that all farm workers make use of electricity, 60 % use gas and 60 % use wood.

3.3.1.5 On-farm generation of electricity

40 % of participants stated that the main reasons why they do not invest in generating their own electricity is that it is too expensive to install a new electricity generating process, 40 % had insufficient knowledge, 20 % preferred the convenience of Eskom and 10 % found investing in new processes too time consuming. No participants implied that technology cannot be implemented on their farm (Figure 6). Participants were able to choose more than one answer.

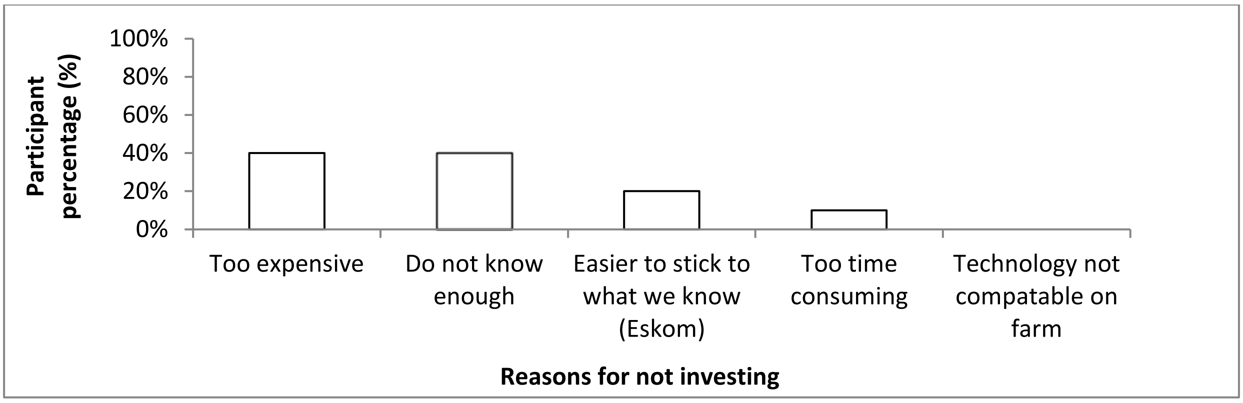

Figure 6: Main reasons why S1 participants do not invest in generating their own on-farm electricity.

3.3.1.6 Awareness of benefits regarding biogas generation

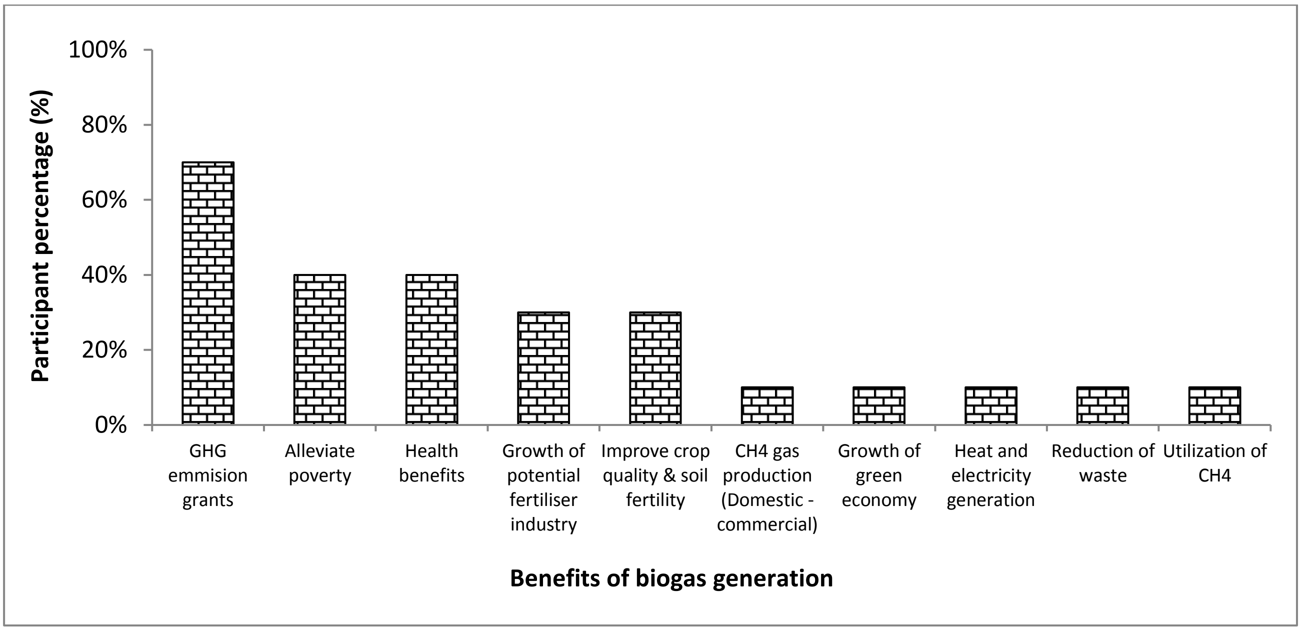

Figure 7: The percentage of S1 participants that was unaware of 10 given benefits of biogas generation.

The S1 survey suggested a list of 10 potential benefits derived from biogas generation: 70 % were unaware of greenhouse gas emissions grants; 40 % were unaware of the potential of biogas generation to alleviate poverty; 40 % were unaware of potential health benefits, 30 % were unaware of its potential in the fertiliser industry; 30 % were unaware of its potential to improve crop quality and soil fertility, 10 % were unaware of the potential of methane gas production on commercial or domestic scale, 10 % were unaware of the potential growth of the green economy (job creation/skill development), 10 % were unaware of its potential to generate heat and electricity, 10 % were unaware of its potential to reduce waste (over-capacitated landfills) and 10 %, were unaware of the potential to utilise methane gas.

3.4 Results for S2 participants – farmers with biogas digesters

3.4.1 Basic overview of digester characteristic, electricity demand and financial feasibility of participants

Table 2 gives an overview of the characteristics of digesters installed by the farmers, the purpose of the digester, as well as the financial feasibility of the operation according to the participants. The identities of the participants, together with some financial values are confidential on request.

The participants also stated that the majority of these projects were not subsidised in any way by the government or government incentive driven program, with the exception of one digester, which was funded by external investors. All participants who use their biogas to generate electricity do not get any financial rebates from government for GHG mitigation.

Furthermore, 40 % of participants were introduced to biogas digesters (BD) by a South African biogas digester company, 40 % were introduced to biogas digesters in another country, and 20 % heard about it by a friend/colleague/family or none of the above. However, none of the participants consulted online sources (Figure 8). Participants could choose multiple answers.

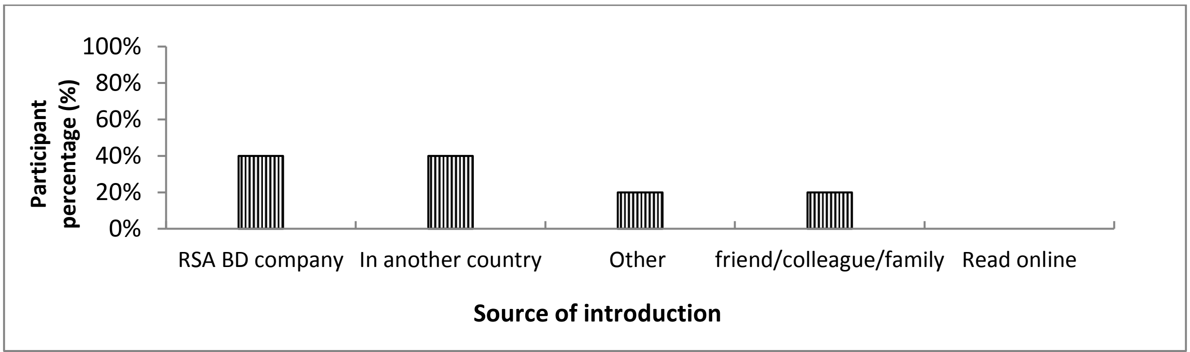

Figure 8: S2 participants' first source of introduction to biogas digesters.

Table 2: An overview of the cost, scale, type, application, financial indicators and hindrances experienced by S2 participants.

(**Participant identities and some financial values are kept confidential on request from the farmers*)

Participants	**Start-up cost**	**Scale/ output**	**Digester type**	**Purpose**	**Waste usage**	**Cost savings on electricity per month**	**Major hindrance experienced**	**Electricity is a major expense on the farm**	**Financially viable according to participant**
Participant 1	R 500 000	-	Plug-flow digester	Research	40.248 m^3	-	Constant operation (daily check-ups)	YES	Not at the moment, potentially in future
Participant 2	R 5 million	50 kW	Covered lagoon digester	Electricity generation	150 t	R 22 000	Unpredictability of microbiology	YES	YES
Participant 3	R 6.5 million	190 kW	Dome type digester	Electricity generation	500 t DM	R 72 000	Capital costs too high	YES	NO
Participant 4	R 10 million	400 kW	Plug-flow digester	Electricity generation	3 046 t	R 80 000	Costs to run plant	NO, however it is significant	Not at the moment, potentially in future
Participant 5	-	75 kW	Agitated, not heated, HRT 50	Electricity generation and hot water generation	400 t	Could not determine	Capital investment	YES	YES

3.4.1.1 Feedstock usage, water usage and waste disposal

All S2 participants make use of a single feedstock (either pig or dairy effluent); none make use of co-digestions of varied types of feedstock. The results showed that water usage per digester was minimal, if not zero, due to the high liquid content of the the wet matter (eg. dairy and piggery effluent). 90 % of participants stated that before implementing a biogas digester, organic waste was disposed through evaporation dams/ anaerobic ponds for fertiliser irrigation/composting/fertiliser. One participant stated that not all manure is diverted to the biogas digester and that manure is still used partially as fertiliser.

3.4.1.2 Fertiliser usage and digestate utilisation

40 % of S2 participants felt that fertiliser is major expense on the farm. 60 % of participants use additional manure/WWTW sludge as soil conditioner for soil preparation; 60 % use their digestate as by-product from their biogas digester operation as soil conditioner/soil amendment and 40 % do not use their own digestate as soil conditioner/soil amendment, but aim to do so in the future. Only 20 % of participants sell their digestate for fertiliser production.

3.4.1.3 Storage and utilisation of biogas digester by-products (biogas/digestate)

None of the participants stored any products from the biogas digester (biogas/digestate). 60 % of participants use all biogas produced, with only one participant using excess biogas to generate heat.

3.4.1.4 Electricity access

60 % of participants are connected to the national Eskom electricity grid; 40 % stated that their farm workers get access to the products (only electricity).

3.4.2 Participants' opinion of biogas generation potential in South Africa

80 % of participants indicated that, according to their experience, there is potential for medium scale biogas digesters with an output scale of >30 kW and <1 MW (Refer to APPENDIX B for scale guideline). One participant mentioned that there is only potential for small-medium scale operations if feedstock is free and when excess heat is used. Other

participants commented that financial viability of small-scale projects have increased and will continue to increase due to the sharp increases in electricity recently and other participants were positive about the potential of small-scale use of own gas. In contrast, one participant was adamant that biogas projects on this scale are not viable and based his statement on personal experience with an installation that was not cost-effective.

All participants agreed that large-scale projects with an output of >1 MW have potential, providing that the technology is effective. One participant mentioned that the adaptability/ease of operation of small-medium and larger scale biogas facilities makes it possible to relieve peak electricity demands placed on Eskom, and in this way promotes the potential of the industry.

Participants were asked to suggest biogas digester types which, according to them, showed the highest potential on farm level. Participants seemed to revert to experience and recommended what they already have, with suggestions on to existing systems, or exploring the possibilities of co-digestion. Single feedstock AD was reported to be inefficient, but preferred as it is biologically more stable. Participants with projects not meeting their demands and becoming a financial liability were unable to recommend a model with more potential. All participants stressed that the lack of technical transfer and training and skills development in the biogas digester industry hinders its potential growth and development.

3.4.3 Operation and employment

Four out of five participants operate the digester on their own, while one participant employs a dedicated operator. This particular participant showed great frustration with the biogas digester that was not feasible. The survey indicated that on average, two people were required to operate this facility. 60 % of the participants agreed that installation of a biogas digester promoted social sustainability by creating jobs; 40 % disagreed.

One participant in particular stressed that the lack skills for biodigester management could lead to additional financial losses, negatively affecting a farmer's motivation to pursue sustainable agricultural practices.

3.4.4 Benefits experienced

Benefits identified by S2 participants regarding their biogas projects are: treatment of waste to produce very effective fertiliser; heat (hot water) and electricity generation; reduction in

CH_4 (mitigate GHG gas emissions, mitigating climatic change); potential to save when carbon tax is implemented; reduction of pollution especially in terms of waste run-off into nearby ecosystems (such as river systems); presenting opportunities to learn more about AD and biogas digesters. However, none of these benefits are applicable to their operation, as the original aim was to save electricity cost and it is not found to be cost effective at this stage.

3.4.5 Impact of policy and legislation implemented by South African government

In terms of policy and legislation regarding generation of biogas and its by-products locally, 60 % of the participants experience challenges in this regard, as no support is received from the government. The process of environmental impact assessments required for the construction of a biogas digester is very expensive and time consuming, carbon tax incentives are difficult to access for small farm-scale biogas operations and there is an overall lack of understanding and available expertise regarding biogas generation as an option.

One participant confirmed that agricultural policies and legislations in general hinder progressive agriculture practices to grow. The lack of knowledge about relevant legislation was highlighted as a hindrance and could be attributed to the lack of education and opportunities within the agricultural sector, as well as a lack of support by National Regulator of South Africa (NERSA).

3.4.6 Reasons given why farmers do not invest in biogas generation

The primary reasons why other farmers do not invest in biogas generation on small-medium farm-scale was the expense to install a new electricity generating process (100 %); in addition, further stumbling blocks were the lack of education about the field (60 %); familiarity with Eskom-supplied electricity (40 %), the perception that this technology will not work on a specific farm (20 %) and the process is regarded to be too time consuming (20 %) (Figure 9).

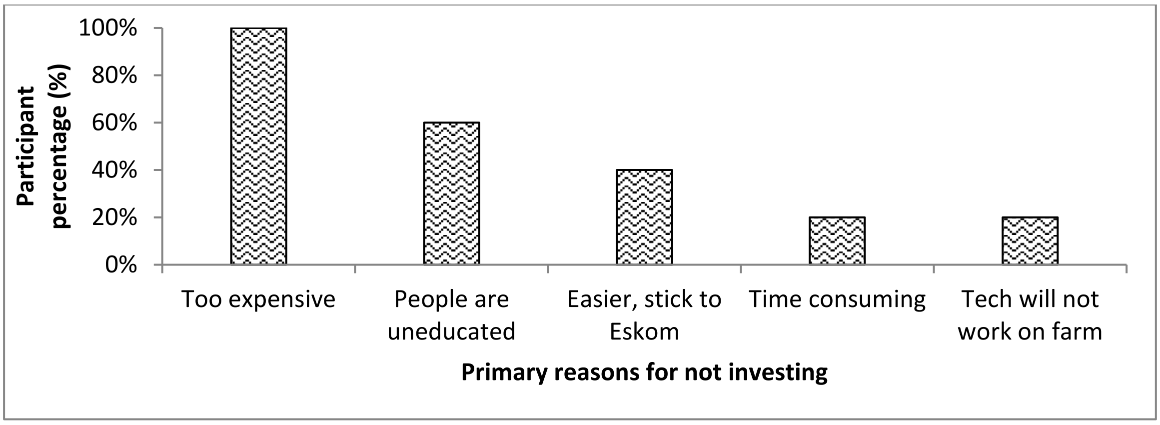

Figure 9: Reasons identified by S2 participants on why they think other farmers do not invest in biogas generation.

4. Discussion

One of the major challenges experienced during this study was to identify and interact with farmers who installed biogas digesters. There are numerous examples of different applications of biogas digesters in South Africa, but only a few instances where it was used solely by farmers. In addition, participants without biogas digesters (S1) were reluctant to participate in this study as they were unfamiliar with the technology, found it not to be applicable to their farming practice and that they thus cannot contribute to the study.

The small group of farmers with biogas digesters (S2) voiced their frustration with their installations. While supporting and understanding the importance of sustainable agriculture practices, the lack of support, experience, skills and confusing legislation were major hindrances in their operations and most of these installations have not reached sustainable feasibility yet, especially with regard to an electricity saving initiative.

The results obtained have been used to evaluate the potential of the agricultural sector to implement the biogas technologies that would enable economic, environmental and social sustainability in this sector. The responses received were interpreted in relation to the three pillars of sustainability as outlined in sections 1.1.1, 1.1.2 and 1.1.3.

4.1 Potential of the agricultural sector to use biogas technology as a means to achieve economic sustainability:

4.1.1 Potential to supply in energy/heat demands by making use of the availability of feedstock

The majority of the S1 participants were aware of biogas digester technology and of the potential to generate energy by using agricultural waste as feedstock. All S1 participants regard electricity as a major expense and a motivation to pursue biogas generation and indicated that they are largely affected by power outages. The perceived time, money and effort of implementing new technology however inhibit these farmers from pursuing biogas technologies, limiting its economic potential. However, everyone agreed that this technology is compatible with their farming practices.

S2 participants identified its potential for waste management and the generation of renewable energy as a definite incentive to pursue this technology. The costs incurred with waste management varied significantly from site to site, and is not seen as a motivation to pursue biogas generation. The significant amount of agricultural wastes that is available to be used as feedstock underscores its economic potential. S2 participants support the potential of the industry if feedstock is free and where excess heat can be used in addition to biogas. According to their responses that not all the biogas produced is used, and 20 % participants use the biogas to generate heat, its full potential in terms of energy generation has yet to be realised.

4.1.2 Potential to produce organic fertiliser that can be used as soil conditioners or compost

Innovative applications of agricultural waste streams as identified by S1 participants indicate that, although they are not yet applying biogas technology, the majority see the potential of agricultural waste streams as a sustainable agricultural practice in terms of fertilising crops, especially as the majority identified fertiliser costs as a major expense. S2 farmers are using digestate, or indicated that they will in future. This supports the potential of biogas generation on farm scale as a mechanism to reuse waste for soil conditioning and to save on fertiliser costs.

4.1.3 Potential to find affordable financial solutions to the challenges of operational costs and revenue possibilities

The results obtained with S2 illustrate that even though these farmers have invested in biogas technology and are saving on electricity cost, capital cost and financial feasibility remains major hindrances in the further development of this industry and limits its economic potential. Where biogas installation occurs as a joint venture between the farmer and the developer (e.g. Zandam farm and iBert) (GIZ and iBert 2017, GreenCape 2017c), the financial risk is reduced and overall financial viability of the project is enhanced (GIZ and iBert 2017, GreenCape 2017c). This approach may promote the economic potential of the farm-scale industry (Bio2Watt 2017, iBert 2017, Scharfy *et al.* 2017).

4.1.4 Potential of accessing realistically available governmental support

The absence of knowledge about a platform of compensation such as governmental incentives or rebates for the generation of environmentally friendly (renewable) electricity known to S1 participants undermines the development of the economic potential of biogas generation. Even though S2 participants invested in this technology, 60 % still identified the lack of government support and the numerous policy and legislation stumbling blocks as factors limiting the potential of biogas generation.

4.2 Potential of the agricultural sector to use biogas technology as a means to achieve social sustainability

4.2.1 Potential to create jobs and opportunities for skills transfer and education

Of the S1 participants a substantial percentage was unaware of the social benefits through the application of biogas technology. Job opportunities reported by S2 participants does not necessarily reflect the job creation potential of the industry as the generation facilities involved are small or farm-scale.

Lack of skills, education and knowledge is however a recurring theme throughout as a limiting factor for the social, economic and environmental potential of biogas generation. This is supported by SAGEN and SABIA (2016) that predicts that this skills gap will expand with the growing market should there be no intervention and standardisation of technical skills.

4.2.2 Potential to deliver health benefits and improve the standard of living

Electricity is the major source of energy for farm workers, together with gas and fire wood. S2 participants indicated that farm workers have access to electricity generated through biogas. Using solid biomass as energy source is however not sustainable (Amigun *et al.*

2012) and creates substantial potential for biogas generation, especially in rural (farming) communities (Smith 2011, Amigun *et al.* 2012, GreenCape 2016, SAGEN and SABIA 2016, GreenCape 2017a).

Tables 3 to 6 quantify the potential of specific feedstocks for energy supply via biogas generation that will result in health benefits and an improved standard of living when implemented.

Table 3: Requirements of digester volume and amount of cattle to produce a certain amount of biogas to supply an associated number of people with energy (Source: Dioha *et al.* 2012).

Required biogas (m^3) for lighting and cooking	**Required number of cattle**	**Required digester volume (m^3)**	**Number of people supplied with energy**
1	2 – 4	4	Up to 4 people
1.5	4 – 5	6	5 – 6 people
2	5 – 7	8	7 – 8 people
2.5	7 – 9	10	10 – 13 people
3.75	9 – 12	15	14 – 18 people
5	13 – 15	20	19 – 25 people

Table 4: Biogas yield from selected feedstock types.

Feedstock	**Daily manure production (kg/animal)**	**% Dry matter (DM)**	**Biogas yield (m^3/kg DM)**	**Estimated biogas yield (m^3/animal/day)**	**Source**
Cow manure	8	16	0.2 – 0.3	0.32	Bond and Templeton (2011)
Chicken manure	0.08	25	0.35 – 0.8	0.01	
Sewage	0.5	20	0.35 – 0.5	0.04	
Pig manure	2	17	0.25 – 0.5	0.128	Surendra *et al.* (2014)
Food waste (Vegetable)	-	5 - 20	0.4	-	Deublein and Steinhauser (2008)
Organic household waste	-	40 - 75	0.3 – 1.0	-	

Table 5: Number of cattle required to produce 1m^3 to generate enough electrical and heat energy.

Feedstock	**Required number of cattle**	**Amount of manure required for 1m^3 biogas per day**	**Biogas yield**	**Electrical energy**	**Heat energy**	**Number of people supplied with energy**
Cow manure	A = 3; B = 2 – 4	25 kg	1 m^3	2.1 kWh	2.6 kWh	Up to 4
Source:	A = Bond and Templeton (2011) B = Dioha *et al.* (2012)	Bond and Templeton (2011)		Arbon (2005)		Dioha *et al.* (2012)

The biogas energy generation analyses (Table 6) is used as additional support for the potential of biogas implementation on farm level to generate and supply energy to farm workers. With as few as 5 to 7 cows, it is possible to supply energy per day for up to eight farm workers (Table 3 and Table 6). When only referring to electricity, it is estimated that 50 kg of cow manure is required from 5 to 7 cattle per day to generate 2 m^3 of biogas with an electrical output of 4.200 kWh. This is similar to the average electricity consumption per capita (4.228 kWh) in South Africa (World Bank 2014).

Table 6: Potential amount of electrical energy generated from biogas produced by the required amount of cattle and manure, compared to the average demand of electricity per capita in South Africa.

Feedstock	**Amount of manure required for 2m^3 biogas per day**	**Required number of cattle**	**Biogas yield per day**	**Electrical energy**	**Average electricity consumption per capita in South Africa**
Cow manure	50 kg	A = 6; B = 5 – 7	2 m^3	4.200 kWh	4.228 kWh
Source	Bond and Templeton (2011)	A = Bond and Templeton (2011) B = Dioha *et al.*(2012)	Bond and Templeton (2011)	Arbon (2005)	World Bank (2014)

Table 7 compares the calorific values of biogas, natural gas, hard coal and firewood and illustrates how biogas generation can replace these sources of energy. Calorific value of fuel is the amount of energy released per unit mass/per unit volume when the fuel is burnt completely (Msibi 2015, em-ea.org 2017).

Table 7: Comparison of calorific value of different energy resources.

Energy resource	Amount required	Calorific value	Source
Biogas	1 m^3	26 MJ 21 MJ 20 MJ	Arbon (2005) Surendra *et al.*(2014) Pathak *et al.* (2009)
Natural gas	0.77 m^3	33,5 MJ	Arbon (2005)
Hard Coal	1.1 kg	23.4 MJ	
Fire wood	2 kg	13.3 MJ	

This illustrates the significant potential of biogas generation to alleviate energy poverty and improve the general well-being of impoverished communities.

4.3 Implementation potential of the agricultural sector to achieve environmental sustainability

Both farmers with or without biogas generation facilities on their farms had a sound understanding of the concept of sustainability and all participants, in both surveys, were positive towards the implementation of sustainability in agriculture. S2 participants were slightly more optimistic regarding sustainable agricultural practices and the role biogas generation plays in sustainable development, while the majority of S1 participants acknowledged that they are not yet living in a sustainable manner. Current efforts by farmers in both groups should be incorporated in future practices, underscores the environmental potential that resides in the agricultural biogas sector.

4.3.1 Potential to contribute to the reduction in greenhouse gas emissions

The level of awareness and understanding of climate change and the negative effects on agriculture were extremely high for both S1 and S2 participants. In addition, S1 participants acknowledged the role that agriculture can play in the production of methane and carbon dioxide. There is no significant lack of knowledge and understanding regarding the generation of methane, the cause and effect of greenhouse gas (GHG) emissions, and the possibility of energy generation through methane utilisation.

Even so, there is no platform for government compensation for reducing GHG emissions, forfeiting the incentive to contribute, as it constitutes too big a financial investment/risk. The majority of (S1) participants indicated that they were not aware of existing financial incentives for curbing GHG emissions. This creates opportunities for future development should these limitations be addressed.

4.3.2 Potential to supply renewable energy

Participants in both surveys indicated that biogas generation would promote sustainability through the provision of a renewable source of energy. S2 participants indicated that they use most of their biogas for the generation of electricity. This supports the potential of this technology to deliver renewable energy, in the case of farm-scale operation this would mostly be appropriated for own use.

4.3.3 Potential to contribute to soil health and increased food production

There is a firm understanding and knowledge of decomposition of organic matter and reutilisation of organic matter as soil amendment. Farmers that installed biogas digesters use digestate successfully as soil conditioner and fertiliser. S1 participants also show understanding of this principle as they apply various innovative methods to use animal and feedstock wastes to enhance soil properties. This underscores the potential of using the by-products of digestate and fertiliser on farm-scale.

Conclusion

According to literature, biogas generation as a sustainable agriculture practice shows very high potential for both energy generation and waste disposal in South Africa (Smith 2011, Abbasi 2012, Amigun *et al*. 2012, Griffiths 2013, GreenCape 2016, SAAEA 2016, SAGEN and SABIA 2016, GreenCape 2017a, Tiepelt 2017). This paper supports this statement.

The willingness/non-willingness of participants to partake in this study, gives insight into the potential of biogas generation in the agricultural sector, as it highlights the limitations on the industry through existing perceptions and frustrations.

Developing the economic potential of biogas generation will require wide-scale knowledge transfer about the opportunities it presents. The availability of financial support, whether in the form of joint ventures, or as incentives or rebates, would enable the industry to grow on farm level. Current waste management practices including the application of waste streams for fertiliser use, supports the potential of biogas generation as a means to generate fertiliser for own use and saving on fertiliser costs.

There is significant promise in using biogas technology to achieve social sustainability, specifically at farm-scale. Job creation, the opportunity for skills transfer and education, as well as the potential to deliver health benefits and improve the standard of living in rural or farming communities, is regarded as substantial.

It is also believed that, through the use of AD, environmental sustainability may be achieved. Participants were familiar with the concept of sustainability and indicated that they would like to follow such practices. The potential of pursuing these activities is however limited by the lack of information about possible rebates in terms of generating renewable energy, rendering installation of biodigesters an unacceptable financial investment/risk.

The limited availability of information, knowledge and skills, however, reduces the potential of this industry. Addressing technology transfer specifically would create significant opportunities to develop this industry in the agricultural sector. This supports various sources reporting the scarcity of experience required to operate biogas plants in order to optimise the country's biogas potential (SAGEN and SABIA 2016, GreenCape 2017a, Mutungwazi *et al.* 2017, Tiepelt 2017).

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PAPER 3: DEVELOPING A DECISION-MAKING TOOL TO EVALUATE THE SUSTAINABLE POTENTIAL OF ON-FARM BIOGAS DIGESTERS IN SOUTH AFRICA

Abstract

Biogas generation and use could potentially impact sustainability, especially through the integration of waste management and energy technologies (Biogas 2013, Bachmann 2015, SAGEN and SABIA 2016). This makes biogas generation especially suitable in the pursuit of sustainable agricultural practices (Biogas 2013, Griffiths 2013, SAGEN and SABIA 2016, GreenCape 2017a, GreenCape 2017b, GreenCape 2017c, Tiepelt 2017). The many variables in the South African scenario complicate implementation, as it was found that implementation should be site-specific to be feasible (Lutge 2010, Biogas 2013, Shah *et al.* *2*014, ESI-Africa 2016, Zhu 2016, GreenCape 2017a, GreenCape 2017c, Mutungwazi *et al.* 2017, Steyn 2017, Tiepelt 2017). A generic model was thus developed as a decision-making tool to enable the evaluation of the sustainable potential of a specific digester type at a specific site, taking all the variables into account. The model is based on the scoring of the three determinants of sustainability namely environmental, social and economic according to a set of four defining factors. Based on literature and local expertise that was accessed through interviews, a comparison of the characteristics of the CSTR digester type with agricultural requirements enabled the identification of the CSTR digester as the type that could show the most sustainable potential when implemented as a sustainable solution to address energy poverty, the rising costs of electricity and waste management demands. The validation of the sustainable potential of the CSTR digester type by applying the generic model is recommended through further studies to enable the successful implementation of this digester type according to site-specific needs.

1. Introduction

There is substantial opportunity for the generation of biogas in South Africa, especially in the agricultural and household waste sector. Renewable energy could provide the much-desired sustainable rural revitalisation in developing countries and also serve as an ideal cost-effective alternative for waste management and energy generation in low-income and/ or rural communities in South Africa, especially as energy has been identified as a major element in the competitiveness and sustainability of the farming sector (Mshandete and Parawira 2009, Smith 2011, Abbasi 2012, Amigun *et al*. 2012, Biogas 2013, Griffiths 2013, NERSA 2013, Carter and Gulati 2014, SAAEA 2016, SAGEN and SABIA 2016, GreenCape 2016, GreenCape 2017b, GreenCape 2017c, Tiepelt 2017).

South Africa has adapted a systems approach to sustainability and is committed to a long-term programme of resource decoupling that would enable the economy to grow without compromising environmental integrity (DEA 2008, DEA 2013). Probably the most important environmental benefits of agricultural biogas use lie in the contribution to reduced CH_4 emissions from the natural decay of organic matter (OM) and in the decrease in CO_2 emissions by using an alternative to conventional fossil fuels (Torquati *et al.* 2014).

The collective self-production of gas in rural and urban households with community-based biogas digesters also show some potential, especially in terms of the relief it can bring to the demands placed on the national electricity grid (NERSA 2013, GreenCape 2017a). GreenCape (2016) estimated that the total electricity potentially generated from biogas in South Africa from agricultural waste is 2 300 MWe (MegaWatt electric). Additionally Abbasi (2012) predicted that by 2020, the largest volume of produced biogas will emanate from farms and large co-digestion biogas plants that are incorporated into farming and food-processing structures.

The task on hand is to identify the production system that has the most sustainable potential and therefore could benefit farmers' quest for a more sustainable future. However, the many variables in the South African biogas generation scenario complicate sustainable implementation, as the design of a digester is influenced by various logistic and social factors such as health and job creation, and therefore it is recommended that farm-scale implementation in South Africa should be tailored to be site-specific (Lutge 2010, Biogas 2013, Shah *et al. 2*014, ESI-Africa 2016, Zhu 2016, GreenCape 2017a, GreenCape 2017c, Mutungwazi *et al.* 2017, Steyn 2017, Tiepelt 2017).

Lutge (2010) further stated that average values tend to mask any potential benefits, particularly when using a function to estimate the cost of a biogas plant, as there are many variables that determine the choice of plant. Mutungwazi *et al.* (2017) concluded that even though their study identified the *in situ*-cast concrete digester (Puxin) as the most suitable digester for energy generation on small/household scale in South Africa, stakeholders should still do their own selection based on the analyses of their own situation and design.

The following digester types were identified as having sustainable potential with regards to biogas generation in the agricultural sector in South Africa: CSTR (continuously stirred tank reactor), lagoon digester, up-flow sludge blanket (UASB), plug-flow digester and fixed-film digester**.** Mutungwazi *et al.* (2017) found the in-situ cast concrete digester (Puxin) to be the most suitable (not necessarily having the highest sustainable potential) small-scale design for installation in the South African context (APPENDIX E).

The choice of the design of the digester is thus a key determinant in the feasibility of its implementation. This paper proposes a generic model to determine the digester type with the highest sustainable potential for different hypothetical sites.

The paper further motivates the CSTR digester type for implementation on farm-scale. The digester type was identified by comparing its characteristics to the requirements of the agricultural sector. This choice of digester type will however have to be validated by applying the proposed generic model on site.

2. Materials and methods

A generic model was conceptualised that could be applied to determine sustainable potential of specific biogas digesters on farms. Face-to-face semi-constructed interviews (Babbie and Mouton 2001) were conducted with key roleplayers in this discipline. These included among others, representatives of the South African Biogas Industry Association (Tiepelt 2017) and GreenCape (2017a), a non-profit organisation that drives the widespread adoption of economically viable green economy solutions from the Western Cape. In addition to available literature including webpages, brochures, policy documents and developer’s implementation specifications, biogas plant developers and installers such as Botala Energy Solutions (Steyn 2017) were consulted telephonically and via email.

Secondly, the characteristics of digester types were considered and compared to the requirements of the agricultural sector to identify the digester type with the highest sustainable potential when applying the generic model on site.

The methodology process followed to develop the model and demonstrate possible implementation is illustrated in Figure 1.

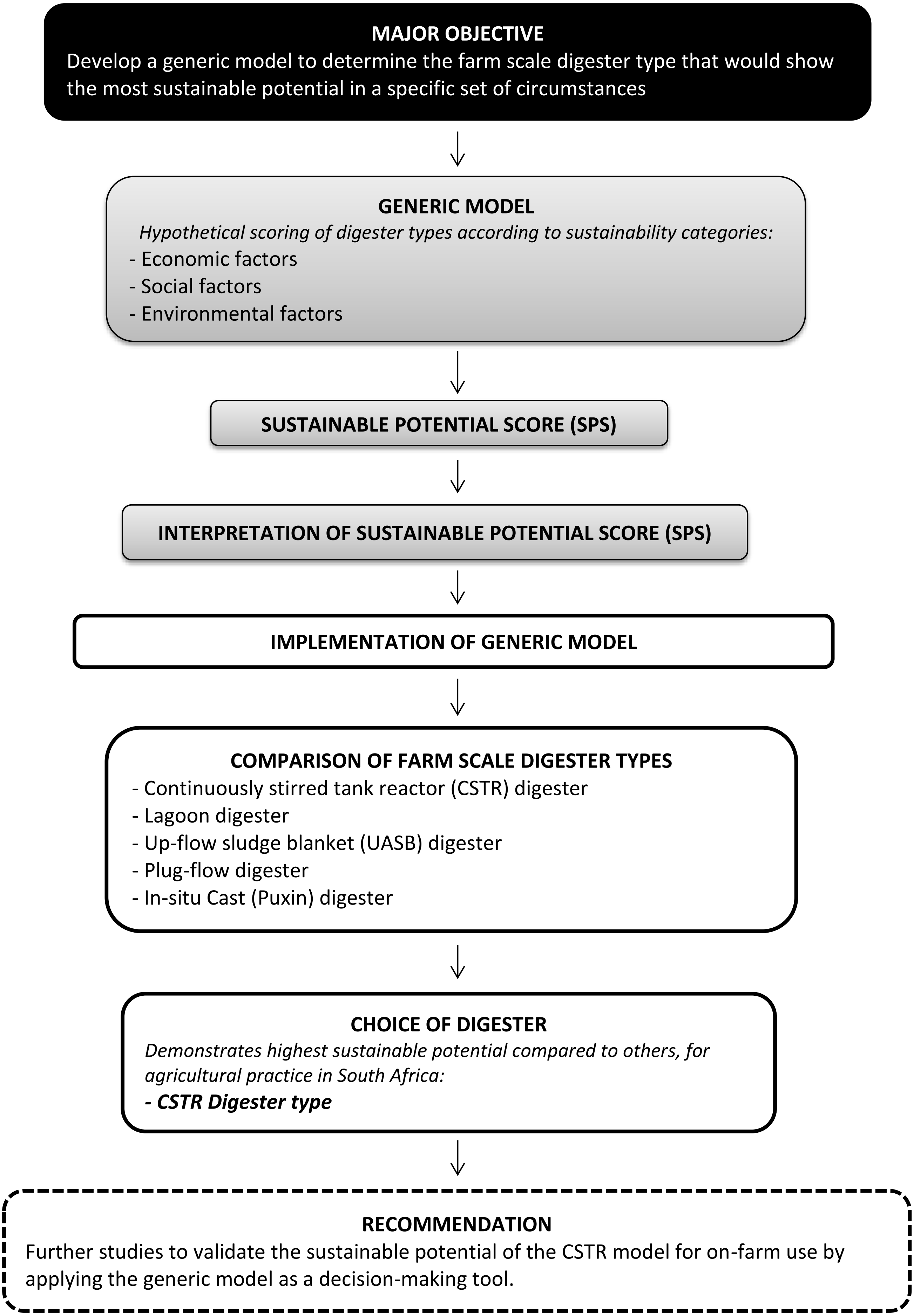

Figure1: Flow chart illustration of the methodology approach

2.1. Constructing a generic model to determine the sustainable potential of a biogas digester for farms

In this study, the development of a generic model to score the sustainable potential of a biogas digester in a site-specific context is based on the hypothetical calculation of sustainable potential. This model focuses on the dynamics of on-farm biogas digester implementation according to the South African situation. While a study by Juarez-Hernandez and Castro-Gonzalez (2016) also made use of a scoring method, it only considered the impact of biogas on the energy sustainability of an urban restaurant in Mexico; Scharfy *et al.* (2017) also calculated scores for three sustainability categories (economic, social and ecology), but for the purpose of evaluating clean technologies in general for agricultural practices in Switzerland.

The first step of this study was defining the three sustainability categories (SC) (i.e. economic, social and environmental) and the factors (SCFs) that impact on each category. (Table 1); secondly, a score out of 5 was allocated for each of these factors (SCFs) within each category (SC) (Table 5). Each digester type was rated out of 20 for its combined economic potential (CEPa), combined social potential (CSP) and combined environmental potential (CEPb) based on the factors determined by literature, which are detailed in Table 1 (Dennis and Burke 2001, Arbon 2005, Jenkins *et al* 2007, Tambone *et al.* 2007, Schleiss and Barth 2008, Tambone *et al.* 2009, Amigun and Von Blottnitz 2010, Lutge 2010, Amigun *et al.* 2011, Dillon 2011, GreenPeace 2011, Smith 2011, Abbasi 2012, Makádi *et al.* 2012, Biogas 2013, DEA 2013, NERSA 2013, EPI 2014, GreenCape 2014, Ruffini 2014, Shah *et al. 2*014, Torquati *et al*. 2014, Msibi 2015, DEA 2016, DoE 2016, ESI Africa 2016, GreenCape 2016, SAAEA 2016, SAGEN and SABIA 2016, Atkins 2017, BiogasSA 2017, Culhane 2017, DEA 2017, GreenCape 2017a, GreenCape 2017b, Kumba *et al.* 2017, Msibi and Kornelius 2017, Steyn 2017, Tiepelt 2017, Tradingeconomics.com 2017).

The total sustainability potential value (TSPV) out of 60 was calculated for each digester. The total sustainability potential percentage (TSPP) is used to determine the sustainability potential score (SPS). The sustainability potential score (SPS) places the biogas digester type in a specific sustainable potential category (SPC) (Table 2), illustrating the digester's sustainable potential.

The equation below illustrates the proposed SPS calculation for a digester type:

$$Digester\ type\ SPS = \left[\frac{(CEPa + CSP + CEPb)}{60}\right] \times 100 \div 20$$

Biogas generation impacts all three principles of sustainability namely environmental, social and economic (Dennis and Burke 2001, Arbon 2005, Greben and Oelofse 2009, Kuhlman and Farrington 2010, Morelli 2011, Potgieter 2011, Smith 2011, Biogas 2013, DEA 2013, EPI 2014, DEA 2016, DoE 2016, SAGEN and SABIA 2016, Teljeur *et al.* 2016, DEA 2017, GreenCape 2017a, GreenCape 2017b, Mutungwazi *et al.* 2017, Tiepelt 2017). Therefore, it is essential to define sustainability, sustainable potential and the categories of sustainable potential used to calculate the sustainable potential of a biogas digester per specific site/environment.

In this paper, sustainability is defined as: "*The process of utilising and living within the limits of available physical, natural and social resources in ways that promote social, ecological and economic sustainability all at the same time, while allowing the living systems in which humans are entrenched to flourish in perpetuity*" (UN 1987, DEA 2008, Kuhlman and Farrington 2010, Morelli 2011, EPI 2014, Uwosh.edu 2017).

2.1.1 Sustainable potential

In this paper, sustainable potential is defined as: "*The possible capacity of using physical, natural and social resources within their available limits and in ways that promote the development and growth of social, ecological and economic sustainability all at the same time, while allowing the living systems in which humans are entrenched to flourish in perpetuity*" (Howarth 2012).

2.*1.1.1 Economic potential*

The economic potential is defined as: *"The subset of the available technical potential that is available in terms of biogas generation, where the cost required to generate the energy (which determines the minimum cost required to develop the resource) is less than the revenue available in terms of displaced energy and displaced capacity"* (Brown *et al.* 2016).

2.1.1.2 *Social potential*

The social potential refers to: "*Social issues and related indicators that can enhance social conditions such as job-creation, health and well-being in South Africa related to the sustainable development of biogas generating facilities"* (Amigun *et al.* 2011, Msibi and Kornelius 2017*).*

2.1.1.3 Environmental potential

The environmental potential is defined as: "*The environmental capacity of structures, processes and functions of ecosystems, bringing together natural physical, chemical, physiographic, geographic and climatic factors, and further integrating these conditions with anthropogenic impacts and activities of concern, to ensure procurement of environmental sustainability*" (Akella *et al.* 2009).

2.1.2 Scoring of sustainable potential methodology

2.1.2.1 Calculating sustainable potential score (SPS)

The hypothetical calculation of potential was done by scoring the three sustainable categories (SCs) based on the four sustainable category factors (SCFs) applicable to each category. The total sustainability potential value (TSPV) is calculated which is a total combined value out of 60 for the combined economic potential (CEPa), combined social potential (CSP) and combined environmental potential (CEPb) of each digester. From the total sustainability potential percentage (TSPP) the sustainability potential score (SPS) is calculated (Table 5) to determine the sustainable potential category (SPC) within which the digester would fall (Table 2).

2.1.2.2 Sustainable Categories (SC) and Sustainable Category Factors (SCF)

Four sustainability category factors are defined for each of the sustainable categories i.e. economic, social and environmental (Table 1).

Table 1: The definitions of the four sustainable category factors (SCF) for each sustainable category (SC) i.e. economic, social and environmental.

SUSTAINABILITY CATEGORY FACTORS DEFINITIONS		
SUSTAINABLE CATEGORY (SC)	**SUSTAINABLE CATEGORY FACTORS (SCF)**	**DEFINITION**
ECONOMIC	*Technical*	Gas production and energy efficiency, temperature sensitivity and water requirements, structure robustness and lifespan, availability of feedstocks
	Fertiliser production	Sufficient amount and composition of fertiliser for own use or resale of soil condition/compost
	Financial	Initial capital cost (including installation) required, operational cost. For example: expected revenues (based on local market prices) minus generation costs, considered over the expected lifetime of the generation asset; or generation costs relative to a benchmark (e.g. a natural gas combined cycle plant) using assumptions of fuel prices, capital cost, and plant efficiency
	Governmental support	Policy and legislation support in terms of subsidies, incentives or programmes, as well as realistic support duration to initiate gas and energy production from installation
SOCIAL	*Job creation*	Amount of jobs created with sufficient job satisfaction, new skills development and training
	Health benefits and energy use	Improvement in living standards, general well-being and access and use of energy sources
	Convenience and access	User friendly and accessible, difficult to use and not so accessible, in-depth training or expertise needed
	Governmental support	Policy and legislation for quality assurance and ability to implement; education facilitation
ENVIRONMENTAL	*GHG mitigating effects*	Sufficient use of biogas generated to decrease greenhouse gasses
	Waste management	Tonnage of waste redirected from landfills or reused
	Fertiliser utilization	Quality composition of fertiliser applicable to environmental standards of fertiliser use
	Governmental support	Renewable resource use and carbon mitigation

2.1.2.3 Sustainable Potential Categories (SPC)

The sustainable potential scores (SPSs) illustrated in Table 5 were used to determine the sustainable potential category (SPC) (Table 2) for each digester type. The sustainable potential categories (SPCs) are defined as follows:

*Note: It is important to note the difference between SC and SCF, refer to section *2.1.2.2*. These definitions are also used for interpretation in section 3.1.2.

- *Poor potential*

Digester type shows poor potential due to a very low sustainable potential score with very poor economic, social, and environmental sustainable potential, and should not be considered.

- *Low potential*

Digester type shows low potential due to a sustainable potential score showing low/fluctuating economic, social, and environmental sustainable potential. Faces many challenges, with room for improvement in certain/all sustainable categories (SC).

- *Average potential*

Digester type shows average potential due to an average sustainable potential score with moderate/fluctuating economic, social, and environmental sustainable potential. Faces some challenges, with room for improvement in a specific sustainable category (SC)/certain sustainable category factors (SCF).

- *Good potential*

Digester type shows good potential due to high sustainable potential score with sufficient economic, social, and environmental sustainable potential. Faces few challenges, with small adjustments needed for improvement in certain sustainable category factors (SCF). Could therefore be considered for implementation.

- *Excellent potential*

Digester type shows excellent potential due to a very high sustainable potential score with combined economic, social, and environmental sustainable potential. Faces no/very little and should be implemented.

2.1.2.4 Sustainable Potential Score Categories (SPSC)

Five sustainable potential score categories (SPSC) are proposed assigning a value range to the sustainable potential category (SPC) against which the SPS per digester type is measured indicating its sustainable potential. To measure the sustainable potential of each SC (economic, social and environmental), the CEPa/CSP/CEPb values can be analysed to determine the SPS for each SC respectively to determine which SC is underscoring and requires improvement to in essence improve the score of each SC and therefore improve the over-all SPS of a digester type. These same measurement categories (SPSC) (Table 2) of potential can also be used to rate the value (out of 5) given to each SCF.

Table 2: Illustrates the five sustainable potential score categories SPSC against which the SPSs are measured for each digester type.

Sustainability potential score categories (SPSC)			
Economic potential category factor	**Social potential category factor**	**Environmental potential category factor**	**Sustainability potential category (SPC)**
1–1.9 Poor	1–1.9 Poor	1–1.9 Poor	1–1.9 Poor
2–2.9 Low	2–2.9 Low	2–2.9 Low	2–2.9 Low
3–3.9 Average	3–3.9 Average	3–3.9 Average	3–3.9 Average
4–4.9 Good	4–4.9 Good	4–4.9 Good	4–4.9 Good
5 Excellent	5 Excellent	5 Excellent	5 Excellent

2.2 Identifying the most sustainable digester type to enable the implementation of the generic model

A comparison of characteristics of biogas generation (Table 3) enabled the evaluation of these characteristics against the requirements of the agricultural sector. This facilitated the identification of the most suitable digester type for agricultural application on a selected site, by applying the generic model (Table 5).

2.2.1 Comparison of characteristics

There are numerous digester types applicable to farm scale AD (APPENDIX E) that varies in efficacy and feasibility (Hamilton 2014). Levels of efficiency also vary between reactor types and specific situations (Lutge 2010, Hamilton 2014, GreenCape 2017a). Tables 3 and 4 compare the characteristics considering feedstock, Hydraulic Retention Time (HRT), biogas yield, difficulty of technology and operational mode.

Table 3: A comparison of the characteristics of digester types considered in this study (Source: De Mes *et al.* 2003, Kelley 2009, Affiliated Engineers Inc 2014, Hamilton 2014, Matheri *et al.* 2016, Mutungwazi *et al.* 2017).

Type	**Feedstock**	**HRT (days)**	**Biogas yield**	**Technology Difficulty**	**Operational mode**
Continuously stirred tank reactor (CSTR)	Slurry manure, abattoir waste and food waste Optimum: 3 % - 10 % total solids Wet digestion	15 - 30	Good	Medium	Low-rate system
Lagoon digester	Liquid (flush) manure Optimum: 0.5 % - 3 % total solids Wet digestion	20 - 200	Poor	Low	Passive system
Up-flow sludge blanket (UASB)	Liquid waste Optimum: low solids influent Wet digestion	0.5 - 2	Good	High	High-rate system
Plug-flow digester	Thick manure only Optimum: 15 % - 20 % Wet digestion	20 - 40	Poor	Low	Low-rate system
Fixed-film digester	Liquid (Dilute waste streams) Flush manure handling Pit-recharge manure collection Optimum: <5 % total solid waste	1-20	Good	Medium	High-rate system
In-situ cast concrete digester (Puxin)	Sewage and food waste	30-40	Moderate (compared to other small scale)	Low	High-rate system

Table 4: Positive and negative characteristics of each digester type (Source: De Mes *et al.* 2003, Kelley 2009, Affiliated Engineers Inc 2014, Hamilton 2014, Matheri *et al.* 2016, BiogasSA 2017, GreenCape 2017a, Mutungwazi *et al.* 2017, Steyn 2017, Tiepelt 2017).

Digester type	**Positive characteristics**	**Negative characteristics**
Complete mix digesters - Continuously stirred tank reactor (CSTR)	Effective agitation; manure kept in suspension Most popular AD technology worldwide; 80 % of digesters installed in South Africa are CSTR; high level of experience with CSTR digesters globally and in South Africa Ability to handle wide range of concentrations and influent total solids; very successful for co-digestion Wide range of application (abattoirs, food processing, fruit and vegetables, manure) Used with scrape/flush systems and dairy/swine systems Good HRT (15 – 30), commonly holds 15 – 20 days' worth of manure and wastewater Good HRT enables establishment of effective contact of bacteria and substrate with high and consistent biogas production Most effective and flexible technology; economically predictable Consistent to manage; with medium degree of technical difficulty	Has to be heated Poor biomass immobilisation Mechanical mixing requirement Digester size can be an issue at lower solids concentrations, thus greater volume required thus larger digester High capital cost Need for periodic maintenance of mechanical parts of digester
Lagoon digester	Waste storage as well as waste water treatment system Sludge can be stored for 20 years Cheap and effective in reducing odours Good for seasonal harvesting Low tech difficulty Longest HRT No need for heating (depending on location) Low capital requirements Works well with single source substrate Low initial maintenance	Methane production follows seasonal patterns with lowest gas production; Least controlled system Life time maintenance on cover, but cover prone to damage Solids/nutrient accumulation Very costly to heat if required; Gas leakage detected High retention rate (20 – 200 days), slow solid conversion No agitation, bacteria and liquid have limited contact Periodic cleaning needed and maintenance of lagoon is difficult; Not effective with co-digestion Often incomplete digestion and odour elimination

Digester type	**Positive characteristics**	**Negative characteristics**
Up-flow sludge blanket (UASB)	Effluent is often recycled to provide steady upward flow Good biogas yield, with good HRT (30-60 days) Simple design, easy construction and maintenance Low operating cost; high removal efficiency Moderate to low energy demand	Difficult to operate Requires heating High capital cost Highly applicable to industrial waste and sewage
Plug-flow digester	Simple design requiring easy installation and handling Adaptable to extreme conditions at high altitudes with low temperatures Low capital cost; reasonable retention time Does not require mechanical mixing, reducing maintenance and failure rates; Works well with single source substrate Works well with dairy manure and scrape system	No agitation; slow solid conversion; Low biogas production Primary feedstock is manure, limited success with co-digestion; Requires high solids manure (11-14 %) Not compatible with sand bedding 15 % - 20 % solid content required may need extra added material; Constant volume, but produces biogas at a variable pressure
Fixed-film digester	HRT can be <5 days, making for relatively small digesters Short retention time with the ability to retain anaerobic microorganisms within the digester irrespective of the short retention time. Easy construction Moderate operation High biogas yield	Need for periodic cleaning and replacement of the film Plugging of the voids between supporting media is usually a problem when high solids develop within the digester Absence of uniform temperature distribution Feed preparation should contain 1–3 % total solids Some potential biogas is lost due to removing manure solids Slow degradable solids must be removed before manure enters digester which is time consuming
In-situ cast concrete digester (Puxin)	Easy to clean; can be constructed from 60 to 1000m^3 Gas produced under constant pressure Variety of organic feedstocks Ensures long term structural and functional integrity (solid concrete structure) Does not require a lot of people to operate	Household scale (too small for agricultural application, loss in feedstock quality and not meeting energy requirements) Only suitable for installation in areas where the ground is good enough for economic excavation Biogas production limited to small gas appliances, compared to gas yield of medium scale plants processing larger volumes of agricultural waste Periodic cleaning needed

3. Results and discussion

3.1 Analyses and interpretation of sustainable potential results according to hypotheses

3.1.1 Hypothetical calculations of sustainability potential scores (SPSs per digester type per sustainable category factors (SCF)

Table 5: The format of the calculations of hypothetical SPSs of five digester types.

Sustainability potential score per digester type per sustainable category factors						
Sustainability category	**Sustainable Category Factors (SCF)**	**Digester type**				
		Digester A	**Digester B**	**Digester C**	**Digester D**	**Digester E**
Economic	Technical factors	3	3	2	1	5
	Fertiliser production	2	3	1	1	5
	Financial requirements	4	2	2	1	4
	Government support	1	3	1	1	5
	CEPa (20)	**10**	**11**	**6**	**4**	**19**
Social	Job creation	2	5	3	2	4
	Health benefits	2	5	2	3	5
	Convenience and access	6	5	1	1	5
	Government support	2	4	1	4	4
	CSP (20)	**12**	**19**	**7**	**10**	**18**
Environmental	GHG Mitigation	5	5	2	5	5
	Waste management	4	5	3	4	5
	Renewable resource utilization (Energy and fertiliser)	3	4	2	5	5
	Government support	4	3	1	1	4
	CEPb (20)	**16**	**17**	**8**	**16**	**19**
TOTAL sustainability potential value (TSPV) (60) per digester		38	47	19	30	56
TOTAL sustainability potential percentage (TSPP) per digester (%)		63 %	78 %	32 %	50 %	93 %
Sustainability potential score (SPS) (%/20)		**≈ 3.2**	**≈ 3.9**	**≈ 1.6**	**≈ 2.5**	**≈ 4.7**

Table 6: Hypothetical SPS and final SPC for each digester type.

Digester type	**Sustainability potential score (SPS)** (Table 5)	**Sustainability potential category (SPC)** (Table 2)
A	3.1	Average
B	3.9	Average
C	1.6	Poor
D	2.5	Low
E	4.7	Good

3.1.2 Interpretation of sustainable potential results

When analysing the data, it is important that the SPS is calculated to one decimal (Table 5), as it can influence the SPC of the digester and will result in critical information regarding the CEPa, CSP and CEPb values left disregarded. A SPS of 3.9 (for example digester B) is very similar to a SPS of 4, indicating that the digester has good potential. However, when referring to the definition of average potential (SPS 3–3.9), the digester shows moderate/fluctuating sustainable potential; indicating a fluctuating difference in the CEPa, CSP and CEPb values, resulting in the digester type not being classified as having "good sustainable potential".

According to the definition of sustainability and sustainable potential (section 2.1.1), the digester type should meet the requirements of all three pillars (economic (CEPa), social (CSP) and environmental (CEPb)). In this case the CSP (19) and CEPb (17) values are relatively high, whereas the CEPa (11) value is lower and identified as an outlier. Thus, digester B would have a SPC of "average potential" stating that "*Digester type shows average potential due to an average sustainable potential score with moderate/fluctuating economic, social, and environmental sustainable potential. Faces some challenges, with reasonable room for improvement in a specific sustainable category (SC)/certain sustainable category factors (SCF).*"

To establish why digester B (for example) only has an average sustainable potential, SC potential should be considered. To determine the sustainable potential of each SC, the CEPa/CSP/CEPb values can be divided by four (as there are four SCFs). Then it is possible to identify the SC with the lowest values. This can be addressed by improving the SPS of a specific SC and improve the over-all SPS of the digester type. Table 7 shows how the SPC for each SC of digester B is measured as an example, followed by how to interpret the economic potential specifically for this digester type based on its hypothetical scores.

Table 7: Calculations based on the hypothetical results for Digester B (Table 5) to determine the economic sustainable potential.

Sustainable Category (SC)	**Calculation SPS for each SC respectively**	**Sustainable potential category (SPC)**
Sustainable economic potential (CEPa/4SCF)	11/4 = 2.75	≈ 2.8 Low
Sustainable social potential (CSP/4SCF)	19/4 = 4.75	≈ 4.8 Good
Sustainable environmental potential (CEPb/4SCF)	17/4 = 4.25	≈ 4.3 Good

When measuring a specific SC, for example economic potential, the result for the specific SC should then be paired with the corresponding SPC definition to determine the potential of that specific SC.

By referring to section 2.1.1, the SPC for sustainable economic potential (2.8 – Low potential) (Table 7) should be interpreted as *"Digester type shows low potential due to a sustainable potential score showing LOW ECONOMIC, sustainable potential. Faces many challenges, with room for improvement in CERTAIN SUSTAINABLE CATEGORIES (SC)."*

Thus to conclude this example, digester B shows low sustainable ECONOMIC potential compared to the social and environmental SC's, with good sustainable potential. The potential of categories SPSC can also be applied to each SCF to determine specific improvement within each SC. This can then be applied to improve the over-all SPS of a digester type for future implementation.

3.1.3 Motivation of the Continuously Stirred Tank Reactor (CSTR) as the digester type with the highest sustainable potential on farm-scale

The CSTR digester was identified with the highest sustainable potential for on-farm biogas generation (Cavinato *et al.* 2000, Mata-Alvarez *et al.* 2000, De Mes *et al.* 2003, Szűcs *et al.* 2006, Jenkins *et al*. 2007, Hinken *et al.* 2008, Lutge 2010, Manyi-Loh *et al.* 2013, Affiliated Engineers Inc 2014, Enitan 2014, Hamilton 2014, Shah *et al.* 2015, Zafar 2015, Culhane 2017, GreenCape 2017a, GreenCape 2017b, Mutungwazi *et al.* 2017, Steyn 2017, Tiepelt 2017).

This was based on the CSTR meeting most of the requirements (also see APPENDIX F) for sustainable biogas digesters (De Mes *et al.* 2003, Szűcs *et al.* 2006, Jenkins *et a*l. 2007, Manyi-Loh *et al.* 2013, Affiliated Engineers Inc 2014, Enitan 2014, Hamilton 2014, Shah *et al.* 2015, Zafar 2015,Culhane 2017, GreenCape 2017b).

3.1.4 Implementation factors for the on-farm CSTR digester.

The major expense in a biogas generation operation, specifically in South Africa, is the initial capital investment and this is essentially the main reason why it is believed that biogas might not have been economically viable on farms in 2010 (Lutge 2010). However, the trend in setting sustainability goals and new agreements by South Africa and the United Nations (NT 2013, NT 2014, Ruffini 2014, SAGEN and SABIA 2016, Atkins 2017, GreenCape 2017b, UNDP 2017) have led to numerous incentives to promote the industry especially on farms.

Realising that the initial capital investment for a biogas plant is high, with a fairly long payback period of 5 to 8 years, BiogasSA is currently developing a practical and cost-effective solution allowing farmers to participate in the actual construction of the plant reducing costs considerably (BiogasSA 2017).

GreenCape (2017c) stated that the successful business cases are driven by a variety of models regarding feedstock, utilisation of energy for heat and electricity and off-take products. However, the success factors that these business cases have in common include energy savings, waste management savings, robust systems with flexible feedstock and revenue from multiple sources.

Table 8: Estimated comparative costs of proposed CSTR design plants for on-farm biogas generation in South Africa done by BiogasSA and Botala Energy Solutions. (Sources: BiogasSA 2017, Steyn 2017).

Output scale	**Feedstock type (number of animals)**	**CSTR digester and size**	**Feedstock (ton) (Steyn 2017)**	**Total cost estimation (15 % accuracy) (Steyn 2017)**	**Payback period (years) (Steyn 2017)**
Raw gas only	Fruit and vegetable waste	50 x 40m	20 t day^{-1} 7300 $t.year^{-1}$	R3 590 000	5 – 8
60kW	Dairy (300; 20 % collection) and feedlot manure (2000; 20 % collection), and abattoir (10.day^{-1}) waste	30 x 50m	4 $t.day^{-1}$	R2 920 000	7.5
60kW	Dairy (300; 90 % collection) and feedlot manure (2000; 90 % collection), and abattoir (10.day^{-1}) waste	38 x 50m	6 $t.day^{-1}$	R3 820 000	7.5
80kW	Fruit and vegetable waste	29 x 50m	8 $t.day^{-1}$` 2920 $t.year^{-1}$	R3 860 000	5 – 8
80kW	Dairy cow manure (16 000)	45 x 50m	64.9 $t.day^{-1}$ 23700 t. $year^{-1}$	R6 680 000	6.5
100kW	Layer chicken manure (45 000)	43 x 50m	5 $t.day^{-1}$, 13 600 $t.year^{-1}$	R2 370 000	6
120 kW	Dairy manure (900; 80 % collection)	38 x 50m	26 $t.day^{-1}$	R4 920 000	4
150kW	Layer chicken manure (30 000)	47 x 50m	30 t.day $^{-1}$ 10900 $t.year^{-1}$	R 11 280 000	4.5

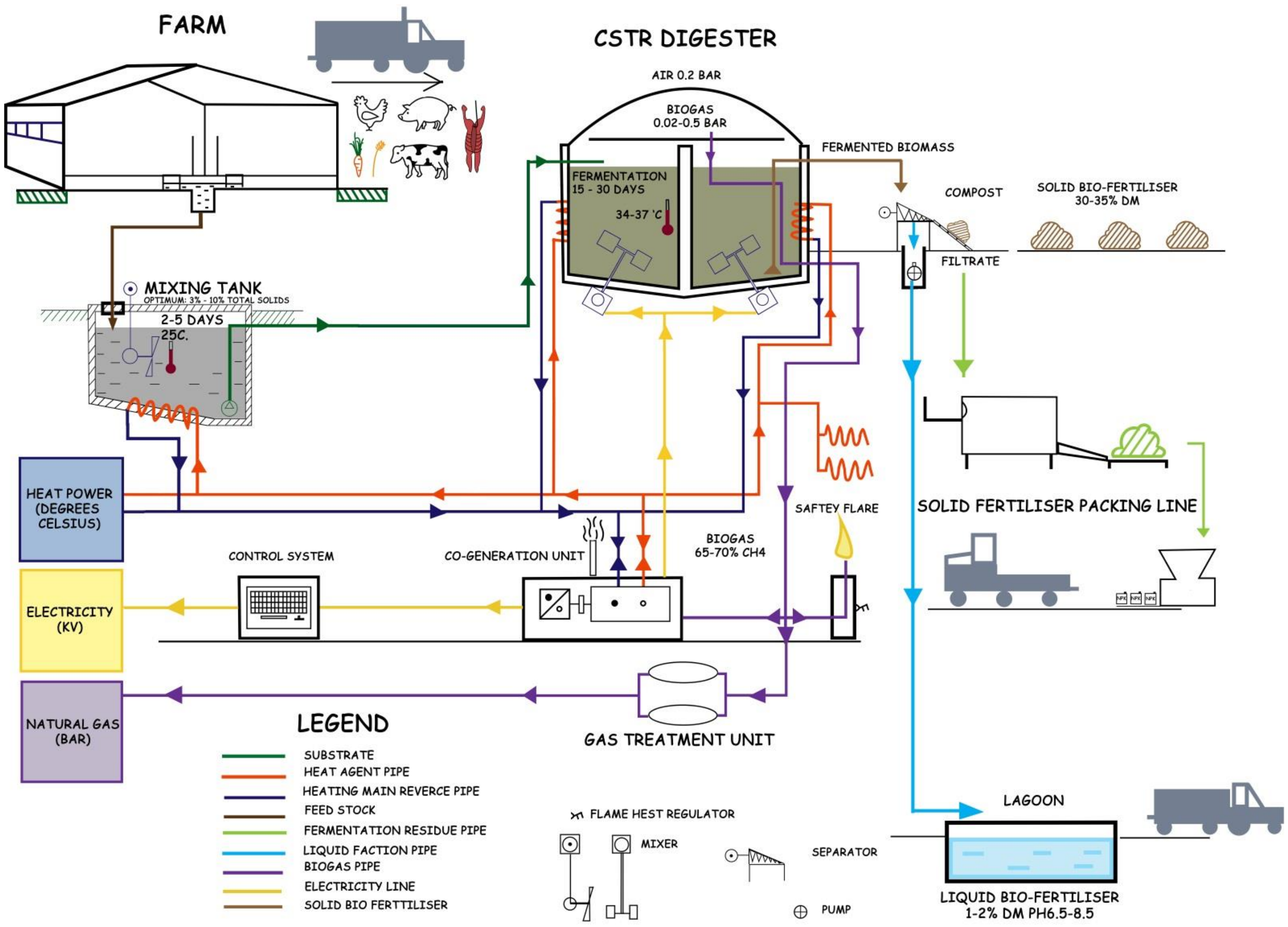

Figure 2: Concept CSTR digester process with the highest sustainable potential for on-farm biogas generation with AD of agricultural waste. (See APPENDIX G for layout and process flow. This diagram was constructed with the assistance of P. Steyn (Managing Director of Botala Energy Solutions, South Africa) and M. du Toit (Architectural drafting)).

Conclusion

There is substantial opportunity in the agricultural sector to apply the available technologies for biogas generation as a sustainable practice. Not only could it stimulate the much-desired sustainable rural revitalisation and address energy poverty, but the highest potential of AD implementation in South Africa is reported to be on farm-scale.

At present, there is no decision-making tool to identify the specific digester type that would demonstrate the most sustainable potential on farms, as there are too many variables such as feedstock availability, legislation, willingness, climatic factors, water availability, and availability of skills and experience, which complicate the implementation of biogas generation. Therefore, a generic model was developed to determine the digester type with the highest sustainable potential according to the specific requirements of a farm.

The generic model is embedded in the concept of sustainability and is based on scoring digester types according to the three categories of sustainability: economic, social and environmental. This presents a unique opportunity to address all three pillars of sustainability according to factors that define each of the sustainability categories. The final numeric value is used to determine the most suitable digester type on site.

In this study, the selection of a digester type was complicated, as it was necessary to integrate the criteria for efficiency and feasibility, as well as the requirements for sustainability. The continuously stirred tank reactor (CSTR) demonstrated the highest potential as sustainable agricultural practice when characteristics were compared against other digester types. However, the validation of this choice was not possible in the scope of this study. Future studies are recommended for application of the generic model on different farms to validate the sustainable potential of different agricultural biogas digester types, and it is recommended that the CSTR digester should be included.

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GENERAL CONCLUSION

New and innovative ways that will enable the agricultural community to farm in a more sustainable manner could contribute to improving South Africa's sustainability standing in relation to other sub-Saharan countries and the world. This potential could be realised specifically with regards to the agricultural waste management sector and in the secure supply of renewable energy, as biogas generation is one of the few technologies that addresses both these issues and that has the potential to improve sustainability on an economic, social and environmental basis. Biogas generation as an alternative renewable source of energy could potentially mitigate the effects of climate change, enable the country to meet peak electricity demands as it is not dependent on resources like wind or water, and can be implemented on any site where waste feedstock is readily available.

By investigating the biogas digester industry in South Africa, it was found that the interest in the development of medium and commercial-scale biogas digesters can be attributed to opportunities that the biogas industry offers in terms of job creation, energy provision, carbon mitigation, organic fertiliser production and waste management. The study confirmed that, while the biogas digester industry in South Africa is currently faced with numerous challenges in terms of renewable energy generation and supply, e.g. a lack of government support, financial commitments involved in its development, skills shortages, ethical challenges, limited water resources and sustainable access to waste as a biomass source, innovative enablers exist that can promote the growth of the industry. By applying enabling factors such as streamlining EIA processes and licencing, biogas generation could provide tax relief through the anticipated implementation of carbon tax, and offer inventive solutions for waste management, while delivering ecosystem services and improved water and soil quality which may result in increased in food production.

Substantial opportunity exists, also in the agricultural sector, to apply the available technologies for biogas generation as a sustainable practice. Not only could it stimulate the much-desired sustainable rural revitalisation and address energy poverty, but it is believed that the highest potential of anaerobic digestion implementation in South Africa is on farm scale. Here, farms may benefit through the generation of electricity, as well as costs savings associated with organic waste treatment, storage and transportation.

This study attempted to further define the potential of farm-scale biogas generation as a sustainable agricultural practice in South Africa through interaction with the farming community. Although substantial understanding of sustainability and the economic potential of biogas generation exists, a lack of knowledge, expertise, financial support and incentives were found to be obstacles in the practical implementation of biogas generation limiting the potential in rural areas. Limited knowledge exists about possible rebates in terms of generating renewable energy and the perception of the farming community is that no effective and sufficient platform for government compensation towards a farmer for reducing GHG emissions exist, constituting too big a financial investment/risk. The availability of information, knowledge and skills regarding this industry affects its economic, social and environmental potential. Addressing this issue specifically would create significant opportunities to develop the potential of this industry in the agricultural sector.

This notion supports recent literature and expert opinions in the field that South Africa lacks the operational experience and skills that is needed to optimise the country's biogas potential. Developing the economic potential of biogas generation will require wide-scale knowledge transfer about the financial opportunities that it presents to supply for energy and heat demands of agricultural operations and the role that the availability of feedstocks play in the realisation of this potential. The availability of financial support, whether in the form of joint ventures between developers and farmers, or as incentives or rebates applied for the generation of renewable energy, will enable the industry to grow. This will allow the farming community to overcome the financial hindrances and perceived risks that currently prevents them from pursuing new technology.

By further investigating the sustainable potential of specific biogas digesters applicable as sustainable agricultural practices, it was found that it is not possible to identify one specific biogas digester type that would demonstrate the highest potential in an agricultural sustainability context, as there are too many variables. It thus became apparent that the choice and implementation of a biogas digester on a farm should be site-specific to be feasible.

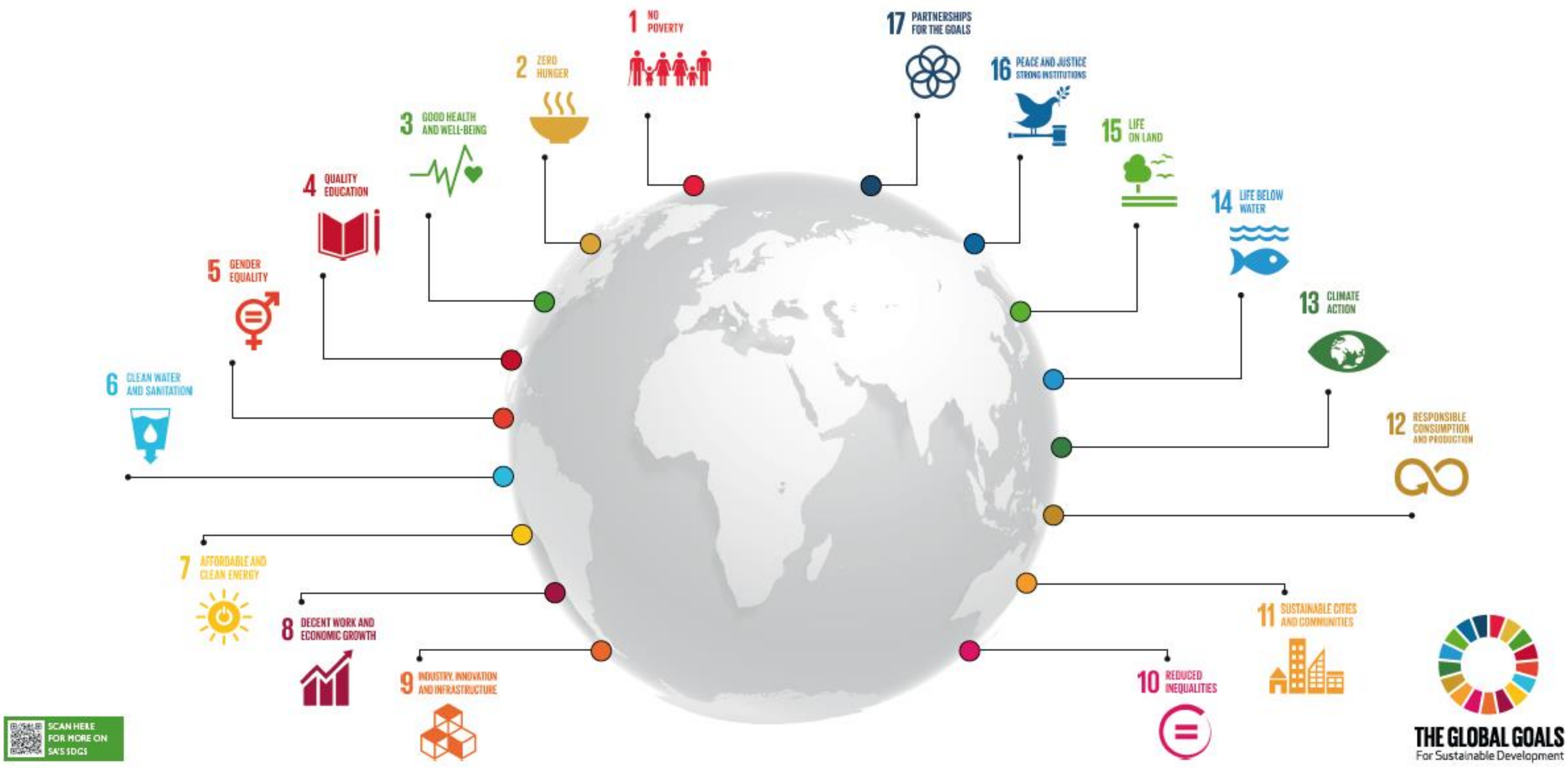
At present, there is no decision-making tool to identify the specific digester type that would demonstrate the most sustainable potential on farms. Therefore, a generic model was developed to determine the digester type with the highest sustainable potential according to the specific requirements of a farm. The generic model is embedded in the concept of sustainability and is based on scoring digester types according to the three categories of sustainability: economic, social and environmental. This presents a unique opportunity to address all three pillars of sustainability according to factors that define each of the sustainability categories. The final numeric value is used to determine the most suitable digester type on site. In this study, the selection of a digester type was complicated, as it was necessary to integrate the criteria for efficiency and feasibility, as well as the requirements for sustainability. The continuously stirred tank reactor (CSTR) demonstrated the highest potential as sustainable agricultural practice when characteristics were compared against other digester types. However, the validation of this choice was not possible in the scope of this study. Future studies are recommended for application of the generic model on different farms to validate the sustainable potential of different agricultural biogas digester types, and it is recommended that the CSTR digester should be included.

The study also clarified that the major expense in a biogas generation operation, specifically in South Africa, is the initial capital investment and this is essentially the main reason biogas generation on farm-scale has not been viable till now. Taking the current Eskom tariff together with the escalation of the Eskom tariff over the next five years into account, biogas plants may only break even after approximately 4-5 years, and start to pay back after 7-10 years, making it not immediately viable on a farm-scale if the motivation to implement biogas digesters is primarily based on pay-back returns for the generation of electricity. However, by applying this technology to generate energy and heat for own use on site, and viewing it as a mechanism to save costs on waste management and fertiliser supplies, biogas generation could be implemented as a sustainable agricultural practice contributing not only to rural revitalisation but also to environmental health and subsequent food production.

To conclude, although numerous challenges impede the potential of biogas generation in South Africa at present, the potential of biogas generation to contribute to sustainable development was quantified and it was found that there is substantial opportunity for government intervention as a means to promote sustainability, not only on farm-scale but also to the benefit of the country as a whole.

APPENDICES

APPENDIX A: The Global Sustainable Development Goals, United Nations Development Programme (Source: UNDP 2017)



APPENDIX B: The plant capacity and scale of biogas digesters in use in South Africa (Source: Smith 2011, SAGEN and SABIA 2016, BiogasSA 2017, Mutungwazi *et al.* 2017, Tiepelt 2017).

Scale	Location	Energy generated	Use of energy	Tonnage and feedstock required	Types installed	South African sites (developers)
Large	abattoir feedlot agricultural processing WWTW	>1 MW	Self-consumption heating or electricity generation (fed into the grid)	15-150 t of MSW per year: manure/abattoir/ WWTW (typical feedstock)	Lagoon type digesters Large-scale mixed-waste CSTR AD system	Bronkhorstspruit (Bio2Watt) Uilenkraal (CAE & Morgan) Abattoir Springs (BiogasSA)
Medium	farms communities breweries restaurants schools	>30 kW and <1 MW	Self-consumption, heating or electricity generation (possibility to feed into grid)	2-15 t of MSW per year: manure / agricultural / abattoir / sewage (typical feedstock)	Lagoon digester, plug-flow digester, complete mix digesters, up-flow sludge blanket digester (UASB)	Jan Kempdorp (Ibert, WEC)
Small	households small farms	<30 kW	Self-consumption, heating or electricity generation	0,1-2 t of MSW per year: manure / sewage (typical feedstock)	In-situ cast concrete digester (Puxin), brick and mortar fixed-dome digester, floating dome digester, plug-flow digester	Waste to Energy Programme (SANEDI, Agama & BiogasSA)
Rural/ domestic	off- grid, rural communities individual households low income households	<10 kW	Supply energy for cooking, lighting or sanitation in rural residential areas, e.g. household with two cows	<1 t of MSW per year: manure or sewage (typical feedstock)	In-situ cast concrete digester (Puxin), brick and mortar fixed-dome digester, floating dome digester, DIY biobag digester kit, LGM rotor moulded in-ground household digester, EZ-Digester, *African green energy technologies (AGET) 10m^3 and AGET 2.5m^3 portable digester*	EZ-digester (BiogasSA)

APPENDIX C: Survey 1 (S1) – Famers without biogas digesters

Evaluating the sustainable potential of Biogas generation in South Africa

Surveys for farmers **without** biogas digesters

GP Jordaan 16463978@sun.ac.za

MSc Sustainable Agriculture

University of Stellenbosch

Name:

Name of Farm:

Location:

Please highlight selected answer:

(Yes/No)

(a) I think this is the right answer

(b) I think this is the wrong answer

Please type answer in **red where applicable.*

Sustainability

1) Have you ever heard of the term sustainability? (Yes/No)
2) Do the terms “organic” and the “sustainability” mean the same thing to you? (Yes/ No)
3) How would you define sustainability with regards to the following definition “Process of utilizing and living within the limits of available physical, natural and social resources in ways that promote……?
   a. social sustainability.
   b. ecological sustainability
   c. economic sustainability.
   d. A and B
   e. B and C
   f. A and C

g. A, B and C

4) Sustainability takes into account ecology, economy and social sustainability? (True/False)
5) Do you feel there is a need for farmers to incorporate more sustainable practices in South Africa? (Yes/No)
6) Do you feel that there is a consumer's demand for incorporate more sustainable practices in South Africa?(Yes/No)
7) Do you feel the electricity crisis in South Africa affects your agricultural practice? (Yes/No)
8) Do you feel that generating environmentally friendly electricity promotes sustainability for a country? (Yes/No)
9) Do you think you are living in a sustainable manner? (Yes/No/ Not yet, but I am trying)

Biogas digesters

1) Do you have a working biogas digester on your farm? (Yes/No)
2) Have you ever heard of a biogas digester? (Yes/No)
3) Have you ever worked with a biogas digester before? (Yes/No)
4) Are you aware of climate change? (Yes/No)
5) Are you aware of any negative influences that climate change might have on your agricultural practices? (Yes/No);

   If Yes please list these influences below:

   …………………………………………………………………………………………
   …………………………………………...……………………………………………
   ……………………………………..

6) Did you know that Methane (CH_4) and Carbon dioxide (CO_2) are some of the biggest contributors towards climate change? (Yes/No)
7) Are you aware of the fact that agricultural activities produce unwanted human derived gasses such as Methane (CH_4) and Carbon dioxide (CO_2) in large uncontrollable quantities? (Yes/No)

8) The global population is growing (expected 9billion in 2050), yet people need to eat; Do you think it is too late for farmers to farm more sustainably? (Yes/No)
9) Define what you think a biogas digesters is, by choosing one option below:
   a. Food digester system in your kitchen which works on biogas to reduce Methane (CH_4) in domestic households.
   b. Simple process which facilitates the natural anaerobic decomposition of organic material to catch up Carbon Dioxide (CO_2) and Methane (CH_4), and uses the methane to generate energy in the form of gas electricity.
   c. Machine which makes use of biological gas in the form of Methane (CH_4) to drive the engine of a vehicle.
   d. Large wind turbines which generate biogas to contribute towards more sustainable living and reduce carbon dioxide (CO_2) and Methane (CH_4)
   e. I have no idea what a biogas digester is.

10) What agricultural activities do you practice on the farm? (………………………………………………………………………………………… ………………………………………...)
11) How do you dispose of your agricultural waste?

-

-

12) What is the cost of total waste disposed per month? (…………………………………)
13) What are your major forms of agricultural waste on the farm? You may tick more than one option.
   a. Organic plant waste
   b. Plastics
   c. Animal Manure
   d. Waste water
   e. Animal body part waste
   f. Other

14) Are you aware of ways to get rid of waste on the farm by using biological methods? (Yes/No)

15) Are you aware of the fact that animal waste, organic plant matter and abattoir waste can be used to generate methane which can be used as gas for cooking and heating and to generate electricity? (Yes/No)
16) Do you generate your own electricity on the farm (Yes/No); If yes do you use (solar/wind/hydro/biogas) and do you get any rebates from the government for generating environmentally friendly electricity (Yes/No)?
17) Are you connected to the Eskom electricity grid? (Yes/No)
18) Do you ever struggle with power cuts? (Yes/No); If yes, does it influence your agricultural practices, ultimately leading to financial losses (Yes/No)?
19) How much money do you spend on Electricity per month on the farm? (…………………….)
20) Is electricity a major expense on the farm? (Yes/No)
21) Is fertiliser a major expense on the farm? (Yes/No)
22) Do you make use of raw sewage sludge from Waste Water Treatment Works as a soil conditioner for soil preparation? (Yes/No)
23) Do you make use of any other raw form of manure or sludge as soil conditioner or soil preparation? (Yes/No)
24) What type of energy source do your farm workers use?
    a. Electricity only
    b. Gas only
    c. Fuel wood only
    d. A and B
    e. B and C
    f. A and C
    g. A,B and C
25) What are the main reasons why you do not invest in generating your own electricity?
    a. It is too expensive to install a new electricity generating process
    b. The technology will not work on my farm
    c. It is easier to stick to what we know, Eskom.
    d. It is too time consuming
    e. I do not now enough.
26) From the benefits regarding biogas generation listed below, select the benefits that you were not aware of:
    a. Reduction of waste (over-capacitated landfills)

b. Heat and electricity generation
c. Health benefits
d. Alleviate poverty
e. Methane gas production (commercial or domestic use)
f. Utilization of methane
g. GHG (Greenhouse Gas) emission grants
h. Growth of potential fertiliser industry
i. Improve crop quality and soil fertility
j. Growth of the green economy (job creation/skills development)

Notes and comments:

Thank you for your time and effort.

Your input is of great value towards my study.

APPENDIX D: Survey 2 (S2) – Farmers with biogas digester

Evaluating the sustainable potential of biogas generation in South Africa

Surveys for farmers **with** biogas digesters

GP Jordaan 16463978@sun.ac.za

MSc Sustainable Agriculture

University of Stellenbosch

Name:

Name of Farm:

Location:

Please highlight selected answer:

(Yes/No)

(c) I think this is the right answer

(d) I think this is the wrong answer

Please type answer in **red where applicable.*

Sustainability

10) Have you ever heard of the term sustainability? (Yes/No)
11) Do the terms "organic" and the "sustainability" mean the same thing to you? (Yes/No)
12) How would you define sustainability with regards to the following definition "Process of utilizing and living within the limits of available physical, natural and social resources in ways that promote……?
    a. social sustainability.
    b. ecological sustainability
    c. economic sustainability.
    d. A and B
    e. B and C
    f. A and C

g. A, B and C

13) Sustainability takes into account ecology, economy and social sustainability. True or false?
14) From a farmer's perspective, do you feel there is a need for farmers to incorporate more sustainable practices in South Africa? (Yes/No)
15) Do you feel that there is a consumer's demand for incorporate more sustainable practices in South Africa?(Yes/No)
16) Do you feel the electricity crisis in South Africa affects your agricultural practice? (Yes/No)
17) Do you feel that generating environmentally friendly promotes sustainability for a country? (Yes/No)
18) Do you think you are living in a sustainable manner? (Yes/No/ Not yet, but I am trying)

Biogas digesters

1. Where did you hear about biogas digesters?
   a. I read about it online
   b. By a friend/colleague/family
   c. South African biogas digester company
   d. Heard about it in another country
   e. Other

2. What is the primary type of farming on the farm? (…………………………………………………….)
3. What is the size of the allocated area for agriculture? (…………………………………………….)
4. What type of biogas digester do you have on the farm? (…………………………………………………….)
5. When did you install the biogas digester? (……………….…)
6. Which company did the installation? (………………../self-installation)
7. How many litres of water is used on the farm per month? (…………………………………………………)

8. How many litres of water does the biogas digester use per month? (…………………………………..)
9. In terms of (kW)/(MW), what is the size of your biogas digester? (…………………………...)
10. How much was the start-up cost for your digester/plant? (…………………………………………………)
11. Did you make use of any subsidies or incentives with regards to the installation cost of the digester? (Yes/no); If yes, was this government based support?
12. What is the major raw material source used as feedstock? (…………………………………………..)
13. What is the amount of feedstock (tonnage) used per month? (……………………………)
14. I am using my biogas digester for (Methane gas use/Electricity generation/Soil conditioner/All of the above/non-of the above)
15. Do you make use of all of the biogas produced? (yes/no); If no, what do you do with the excess biogas? (………………………..)
16. Do you generate your own electricity on the farm (Yes/No); If yes do you use (solar/wind/hydro/biogas) and do you get any rebates from the government for generating environmentally friendly electricity (Yes/No)? If Yes, for which type of method do you receive rebates (solar/wind/hydro/biogas)?
17. Do you have a dedicated operator for the biogas digester? (Yes/No)
18. Do you operate the digester on your own? (Yes/No)
19. How many people are employed to work on the biogas digesters? (…………….)
20. How did you dispose your waste before making use of a biogas digester?

21. Is it financially viable to operate a biogas digester on your farm? (Yes/Not at the moment but potentially in the future/No)
22. Do you feel it contributes in terms of sustainability (Yes/No)
23. Do you store any of the products from the biogas digester? (Yes/No). If yes,
    a. What type of product do you store? (gas / digestate/methane)
    b. Describe the type of product chosen in question 20 a?

c. What method of storage do you use?
(…..…………………………………………………………………..)

24. Do the farm workers get access to the products of the biogas digester? (Yes/No); If yes, what type/s of product/s do the farm workers get access to? (Electricity/Biogas/Soil conditioner)
25. Do you feel that by installing a biogas digester it has created new jobs on the farms, thus promoting social sustainability? (Yes/No)
26. Do you feel there is potential for small medium biogas digesters (<30Kw and >1MW) in South Africa? (Yes/No)
    a. Why?

27. Do you feel there is potential for large scale (<1MW) biogas digesters in South Africa? (Yes/No)
    a. Why?

28. What type of biogas digester system would you recommend as the most suitable farm scale biogas digester system for South Africa?
    -

29. List the major benefits are there for you in terms of operating biogas digesters on the farm?

-

-

-

-

30. List one major hindrance regarding the operation of your biogas digester system?
    -

31. In terms of policy and legislation, do you find that there are any hindrances from the government's side? (Yes/No).
    If yes, list these hindrances?
    -
    -
    -
    -
32. Do you think there is a lack of education regarding biogas digester systems? (Yes/No)
33. Do you think there is a lack of skill development in the biogas digester industry? (Yes/No)
34. What is your opinion on the fact that electricity generated by biogas digester systems cannot be connected directly to the grid, where wind and solar energy are able to connect to the grid?

35. Are you connected to the Eskom electricity grid? (Yes/No)
36. How much money do you save by using a biogas digester? (……………………………………/none)
37. Do you ever struggle with power cuts? (Yes/No); If yes, does it influence your agricultural practices, ultimately leading to financial losses (Yes/No)?
38. How much money do you spend on electricity per month on the farm? (………………………..)
39. Is electricity a major expense on the farm? (Yes/No)
40. Is fertiliser a major expense on the farm? (Yes/No)
41. Do you make use of any other raw form of manure or Waste Water Treatment sludge as soil conditioner or in soil preparation? (Yes/No)
42. Do you make use of your own digestate as soil conditioner/compost? (Yes/No)
43. Do you sell your digestate for fertiliser production? (Yes/No)
44. What are the main reasons why other people do not invest in generating their own electricity by using biogas digester systems?
    k. It is too expensive to install a new electricity generating process
    l. The technology will not work on their specific farm
    m. It is easier to stick to what we know, Eskom.

n. It is too time consuming
o. People are uneducated in the field.
p. Other
(……………………………………………………………………………
……………………………………………)

Notes and comments:

Thank you for your time and effort.

Your input is of great value towards my study.

APPENDIX E: Digester types description with specific reference to potential on-farm biogas generation (Paper 3).

The following digester types where identified as having sustainable potential with regards to biogas generation in the agricultural sector in South Africa: CSTR (continuously stirred tank reactor), lagoon digester, up-flow sludge blanket (UASB), plug-flow digester and fixed-film digester**.** Mutungwazi *et al.* (2017) found the in-situ cast concrete digester (Puxin) to be the most suitable (not necessarily having the highest sustainable potential) small-scale design for installation in the South African context.

Complete mix digester - Continuously stirred tank reactor (CSTR)

Complete mix digester is a collective term for hardware that contains, heats and continuously or intermittently stirs/mixes an active mass of micro-organisms inside the digester (Figure 1) (Hamilton 2014). Incoming liquid displaces volume in the digester, and an equal amount of liquid flows out, together with methanogens. Digestion may take place in more than one tank (acid-formers break down manure in one tank, and methanogens convert organic acids to biogas in a second tank). Biogas production is maintained by adjusting volume so that liquids remain in the digester for 20 days to 30 days, but retention can be shorter for thermophilic systems (Hamilton 2014, Mutungwazi *et al.* 2017). Manure is typically heated to maintain a mesophilic or thermophilic environment, often using recovered heat from the biogas burner; these digesters work best when manure contains 3 to 6 % solids (Affiliated Engineers Inc 2014); lower solids mean greater volume, requiring a larger digester to retain the microbes for 20 days to 30 days (Hamilton 2014).

There are three known types of complete mixed digesters: continuously stirred tank reactor (CSTR); completely mixed flow reactor (CMF) and continuous-flow stirred tank (CFST) (Kelley 2009). A CSTR digester has a sealed, cylindrical concrete or steel tank, where feedstock is mechanically kept in suspension by a motor-driven impeller, pump, or other device (Affiliated Engineers Inc 2014). The typical sources of feedstock for CSTR digesters are abattoirs, food processing plants, fruit/vegetable packaging and poultry, pig and dairy farms (Hamilton 2014).

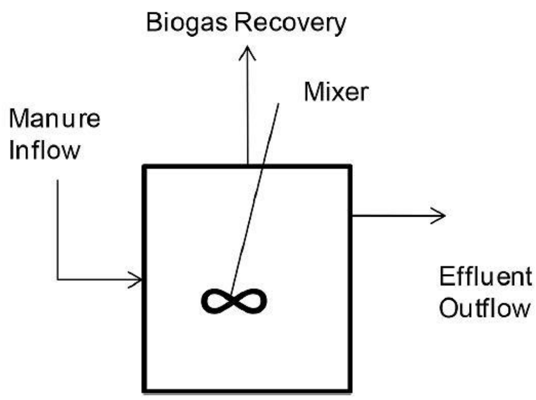


Figure 1 Schematic drawing of a complete mix digester (Source: Hamilton 2014).

Lagoon digester

The lagoon digester has an impermeable cover that contains and traps biogas as anaerobic decomposition of the waste progresses, and while it stores waste it also acts as a waste treatment system. It has two cells, both of which are needed for the system to work at its best (Figure 2) (Affiliated Engineers Inc 2014, Hamilton 2014, Mutungwazi *et al.* 2017). While the first cell is covered, the second cell is uncovered and the liquid level in the second cell rises and falls to create storage while the level on the first cell remains constant to enable decomposition (Hamilton 2014). Lagoon digesters are not heated and are sometimes called ambient temperature digesters as it follow seasonal patterns. While a covered lagoon in the tropics will produce gas all year, methane production drops when temperatures fall below 20°C (Hamilton 2014, Steyn 2017). The methane producing organisms remain in in the covered lagoon for as long as sludge can be stored (which could be up to 20 years) effectively retaining many fertiliser nutrients, particularly phosphorus, in the lagoon (Hamilton 2014). Lagoon covered digesters in South Africa are relatively cheap compared to other on-farm digesters (GreenCape 2017a, Steyn 2017).

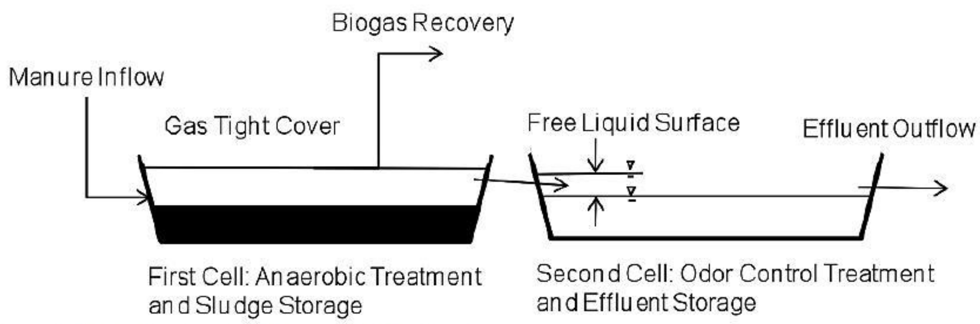


Figure 2: Schematic drawing of a lagoon digester (Source: Hamilton 2014)

Up-flow sludge blanket (UASB)

In an UASB reactor (Figure 3), the influent enters through the bottom of the reactor, enabling contact between the accumulation of microbial biomass in the sludge bed and blanket with the influent (Abbasi and Abbasi 2012, Enitan 2014). USAB digesters is a suspended media digester where microorganisms are suspended in a constant upward flow of liquid, enabling them to form biofilms around the larger particles, and causing the methanogens to stay in the digester (Hamilton 2014).

As UASB reactors are highly dependent on its granular sludge during wastewater treatment to effectively transform organic matter to biogas (Batstone *et al.* 2002, Liu *et al.* 2003, Enitan 2014), some designs include other supporting media, such as sand for microbes to form a biofilm on (Hamilton 2014). These are called fluidized-bed digesters, and flow is adjusted to allow smaller particles to wash out, while allowing larger ones to remain in the digester (Hamilton 2014).

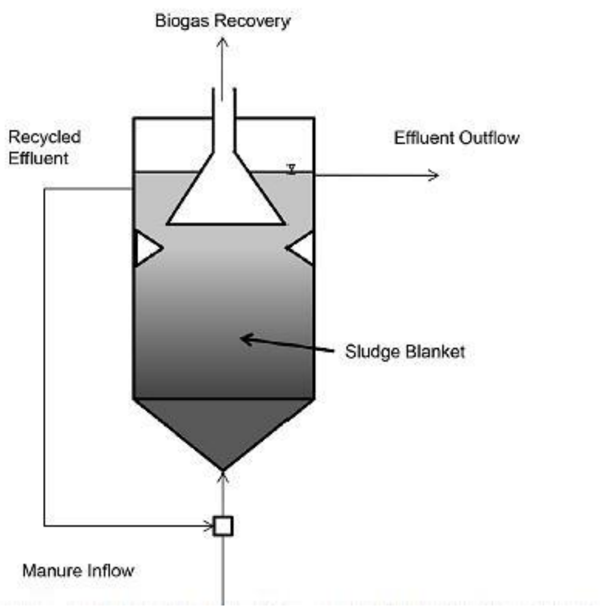


Figure 3: Schematic drawing of an Up-flow sludge blanket (UASB) digester (Source: Hamilton 2014).

Plug-flow digester

The plug-flow digester (Figure 4) is based on a concept similar to a complete mix digester with equal amounts of substrate/manure flowing into and out of the digester (Hamilton 2014, Mutungwazi *et al.* 2017). The digester includes a long and narrow tank with an average width to length ratio of 1:5 (Tervahauta *et al.* 2014), with the inlet and outlet of the digester set at opposite ends above the ground, and part of the digester located underground at an inclined position that enables a two-phase system where methanogenesis and acidogenesis is separated longitudinally (Mutungwazi *et al.* 2017). As no lengthwise mixing of the substrate from inlet to outlet takes place, the substrate flows as a plug and it is thick enough to keep particles from settling to the bottom (Hamilton 2014, Mutungwazi *et al.* 2017).

The digester can be covered with a roof to avoid temperature fluctuations and keep the process temperature (Mutungwazi *et al.* 2017). While the plug-flow digester design, first used in South Africa in 1957, produces biogas at a variable pressure, it has a constant volume (Ghosh and Bhattacherjee 2013, Mutungwazi *et al.* 2017).

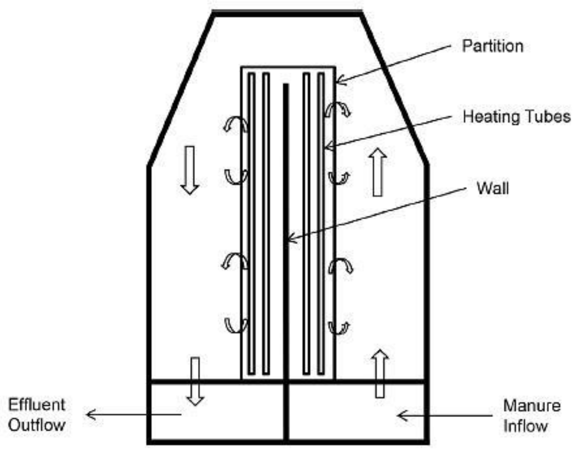


Figure 4: Schematic drawing of a mixed plug-flow digester (Source: Hamilton 2014).

Fixed-film digester

The fixed-film digester (Figure 5) consists of a tank where methane-forming microorganisms grow on supporting media such as wood chips or small plastic rings filling a digestion column, and are also known as attached growth digesters or anaerobic filters (Hamilton 2014,Mutungwazi *et al.* 2017).

As the waste manure passes through the media, biogas is produced (Hamilton 2014). The media supports a thin layer of anaerobic bacteria termed bio-film giving rise to the name of the digester (Ghosh and Bhattacherjee 2013). The immobilisation of the bacteria as a bio-film prevents the washout of slower growing cells and provides biomass retention independent of HRT (Mutungwazi *et al.* 2017).

A solid separator is needed to remove particles from the manure before feeding it to the digester (Hamilton 2014). Like covered lagoon digesters, fixed-film digesters are best suited for diluted waste streams and can be used for both dairy and dairy and swine wastes (Mutungwazi *et al.* 2017).

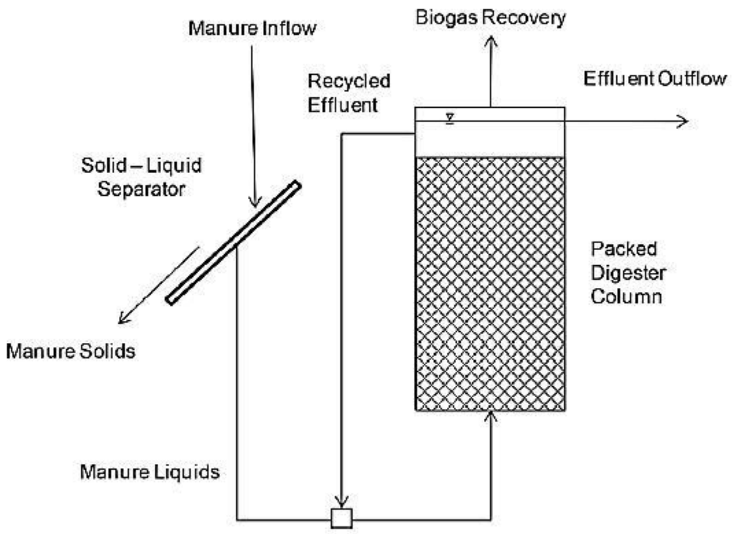


Figure 5: Schematic drawing of a fixed film digester (Source: Hamilton 2014).

In-situ cast concrete digester (Puxin)

The in-situ cast concrete (Puxin) digester is a hydraulic household-scale digester to treat sewage and food wastes, and was designed to solve the technical problems that were experienced with traditional fixed and floating-dome digesters (BiogasSA 2017). BiogasSA is the sole licensee for South Africa of the Shenzhen Puxin Science and Technology Company (Puxin) of China (BiogasSA 2017).

The Puxin is constructed by casting concrete around small bolted steel panels that is stacked in the form of an igloo to form the digester (Mutungwazi *et al.* 2017) (Figure 6), and has a plastic fibre gas holder, neck and belly, and an inlet and outlet pit (BiogasSA 2017, Mutungwazi *et al.* 2017). The entire digester is flooded with water at the same level, and the decay of organic matter takes place under water, creating optimal conditions for AD and the production of methane (Shenzhen Puxin Sci. Tech. Co. Ltd 2015, BiogasSA 2017, Mutungwazi *et al.* 2017).

The gas produced is collected in the dome, and as the volume of gas increases, it shifts the water downwards ensuing in an upward pressure on the gas due to the equal and opposite reaction of the displaced water, ensuring in turn that the collected biogas in the dome is always under constant pressure of up to 8 kPa - a major advantage for running gas appliances (Shenzhen Puxin Sci. Tech. Co. Ltd 2015, BiogasSA 2017, Mutungwazi *et al.* 2017).

The light weight Puxin digester is easy to clean hence any type of organic material can be used as feedstock (Shenzhen Puxin Sci. Tech. Co. Ltd 2015, BiogasSA 2017, Mutungwazi *et al.* 2017).

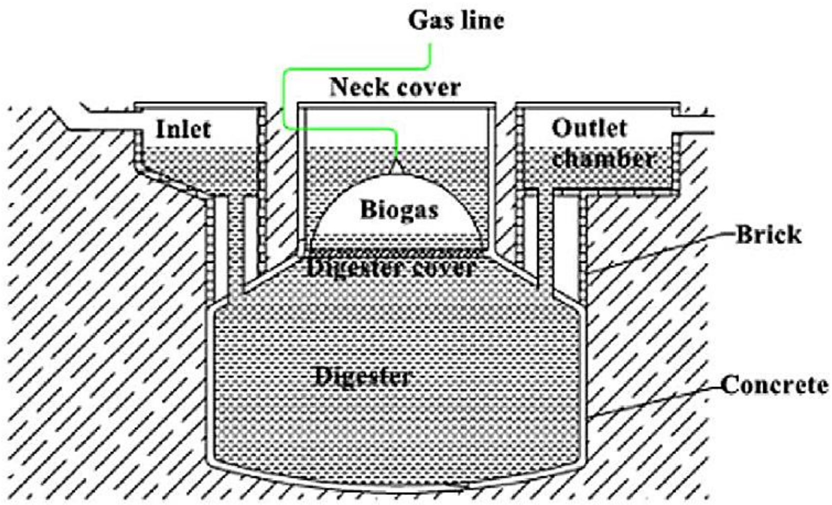


Figure 6: Schematic drawing of an in-situ cast concrete digester (Puxin) (Source: Mutungwazi *et al.* 2017).

APPENDIX F: Biogas generation requirements in the agricultural context matched to the characteristics of the CSTR digester (Paper 3).

Co-digestion capabilities

The CSTR digester is not limited to one source of feedstock but able to digest a wide range of influent total solids and concentrations, and a variety of organic matter, either alone or through co-digestion (Affiliated Engineers Inc 2014, Enitan 2014, Hamilton 2014, Shah *et al.* 2015, Culhane 2017). The co-digestion capabilities of the CSTR digester makes it more economically viable as a variety of agricultural waste streams can be used as feedstock on a single farm; alternatively it can be implemented as a community-based plant making offering the opportunity to farmers to process crop biomass together with animal manures, which is the largest agricultural waste stream (De Mes *et al.* 2003, Zafar 2015, GreenCape 2017b). Co-digestion promotes reactor efficiency and dilutes the inhibitory effects of substances, improves microbial diversity and synergy (which plays an essential role in methanogenesis), balances the micro and macronutrients, supplies missing nutrients from co-substrates such as manures, and increases the methane yields per unit of digester volume (Cavinto *et al.* 2000, Mata-Alvarez *et al*. 2000, De Mes *et al.* 2003, Hinken *et al.* 2008, Shah *et al.* 2015). Studies have also found that biogas production per digester volume can be increased by operating the digesters at a higher solids concentration (Zafar 2015), promoting the fact that CSTR digesters are able to work over wide range of influent total solids (Hamilton 2014), while the addition of plant material with high carbon content balances the carbon to nitrogen (C/N) ratio of the feedstock, thereby decreasing the risk of ammonia inhibition (Zafar 2015).

Ability to use animal manure

The ability of CSTR digesters to use animal manure ensures the safe reuse and transformation of waste into valuable materials and energy (Manyi-Loh *et al.* 2013). This decomposition of animal manure that occurs within a confined area contributes to pollution control as it destroys pathogens by reducing the microbial load to a level which could be safely handled by humans (Jenkins *et a*l. 2007).

Reasonable HRT

Compared to the other digesters, CSTR digesters have a reasonable HRT of approximately 15 to 30 days, increasing the contact time of wastewater with the sludge, and in this way improving the effluent quality and biogas production rate (Szűcs *et al.* 2006, Enitan 2014).

Ability to withstand temperature fluctuations

Steyn (2017) suggests that in terms of seasonal temperature fluctuations in South Africa, a plug-flow or lagoon digester is not recommended as a high sustainable potential option, as winter temperatures constrain the digestion process. In comparison the CSTR is a heated system ensuring constant temperatures at which AD can take place.

Availability of expertise and technology

The CSTR digester design is proven to be the most commonly used and successful anaerobic digestion technology worldwide (Affiliated Engineers Inc 2014) and accounts for up to up to 80 % of digesters installed in South Africa (Mutungwazi *et al.* 2017), and 90 % of newly installed wet digesters (Shah *et al.* 2015). This situation has created numerous opportunities worldwide and in South Africa to build expertise and understanding of this particular technology (Steyn 2017).

Ease of management

The CSTR digester design is regarded as having the highest potential in terms of farm-scale implementation in South Africa (GreenCape 2017a, Steyn 2017, Tiepelt 2017) as it is economically more predictable and consistent to manage (Lutge 2010, Steyn 2017).

APPENDIX G: CSTR digester layout and process flow; maintenance and development (Paper 3: Figure 2).

Layout

Figure 1 shows the key components in the biogas plant: (1) mixing tank, (2) digestion tank, (3) co-generation unit, (4) co-generation unit and electricity distribution system, (5) gas treatment unit, (6) control system, (7) solid bio-fertiliser production, (8) lagoon effluent storing and handling, (9) solid fertiliser packing line and (10) safety flame heat exchange unit. The material flow includes biomass and organic waste as inputs, and electricity, organic fertiliser and heat/hot water as outputs. The biogas plant will produce methane gas, which will be converted into electricity and heat or hot water through a generator. The proposed simultaneous use of both electricity and heat in this model opens a sustainable pathway to reduce extra costs for heating and partial powering of mechanical mixers (GreenCape 2017a, Tiepelt 2017). It is estimated that approximately 90 % of the organic input will come out as enriched liquid fertiliser.

Input

One of the distinct advantages of a biogas plant is its ability to be located anywhere where waste feedstock is available enabling it to contribute significantly to efficient waste management (Biogas 2013, Msibi 2015, SAGEN and SABIA 2016). This makes it particularly suitable for rural areas as the agriculture sector generates mainly organic waste that could be used as feedstock (GreenCape 2016, GreenCape 2017b).

Feedstock can be cow, chicken or pig manure, food waste including oil, fat, fruit and vegetable wastes, all components of slaughterhouse waste, any plant material (except excessive amounts of wood) and human sewage (Enitan 2014, Hamilton 2014, Shah *et al.* 2015, Mutungwazi *et al.* 2017, Steyn 2017). Each type of feedstock should be suitably processed to allow maximum efficiency of the bacterial digestion inside the tank. When feedstock with a very low moisture content is used, fresh water/reused liquid in equal quantities will have to be added (Steyn 2017).

Water scarcity in South Africa should not be seen as a limiting factor as up to 80 % of the liquid can be reused depending of the type of feedstock, reducing the water requirements of a digester substantially (Morales-Polo and del Mar Cledera-Castro 2016, Bansalet *et al.* 2017, Tiepelt 2017). Reutilising the liquid digestate also has its benefits as the temperature of reused digestate is higher and the warmer water creates a more suitable micro habitat for digestion (Morales-Polo and del Mar Cledera-Castro 2016, Bansalet *et al.* 2017, Tiepelt 2017). Each type of feedstock has different digestion characteristics thus requiring different tank sizes and generates different gas yields per tonne, supporting to the site-specific approach (Lutge 2010, GreenCape 2017b, GreenCape 2017c, Mutungwazi *et al.* 2017, Steyn 2017).

Output of the process (biogas, heat and electricity generation)

The gas produced by the anaerobic decomposition process in the digesters is extracted on a continuous basis into the gas treatment unit. The gas is collected from the top of the tank and treated to allow it to be used as a fuel source in various ways. The gas at this stage comprises approximately 60 % to 75 % CH_4 (methane) and various other components (De Mes *et al.* 2003, Shah *et al.* 2014). The unwanted sulphurous (H_2S) component in the gas is removed and excess moisture is taken out of the gas stream. H_2S is removed by a standard air-dosing treatment into the digester head-space which causes sulphur-eating bacteria to consume the H_2S gas (Krayzelova *et al.* 2015). H_2S gas formation can also be very effectively eliminated by adding iron chloride solution into the digester mix tank (Kapdi *et al.* 2005). These components must be removed to protect gas burning equipment from and other stainless steel parts of the generator from corrosion (ISSF 2012).

Once the gas is cleaned it can be used as fuel for a standard internal combustion engine driven generator to produce electricity or gas for heating and cooking appliances, hot water boilers and household geysers (Mihic 2004, Steyn 2017, Tiepelt 2017). Operating the generator at a constant output of 90 % of the peak power ensures full fuel efficiency and energy production (Steyn 2017). The excess heat from the generator exhaust fumes can be collected by an integrated heat recovery system (CHP) to produce steam or hot water for general heating purposes (Naegele *et al.* 2012, Ahmed 2014, Steyn 2017). The total heat energy contained in the hot water is up to 130 % of the total electrical energy produced by the generator and the hot water is regarded as a valuable asset and energy source that should be further applied to increase the energy savings potential of the plant (Naegele *et al.* 2012, Steyn 2017). For electrical generation the correct generator size is selected to optimise the use of the generator and to supply in the maximum power demand of the specific operation. Depending on funds available, multiple smaller generators can also be used for the event of a generator being out of service for maintenance or a breakdown.

Excess biogas is vented through a safety flame which indicates the presence of gas in the system. It is proposed that the safety flame be adjusted manually to ensure that the consistent and correct temperature is maintained when needed, in order to enhance anaerobic digestion during colder conditions times. To speed up the digestion process and save costs on heating, methane generated by the digester can be used to heat the mixture (Balsam 2006, Grelaud 2007, Lutge 2010, Tiepelt 2017).

Apart from electricity generation the gas can also be used to replace LPG usage in appliances where the burner jets have been replaced by jets for natural gas jets in order to obtain the same energy output (Steyn 2017). In the event of the gas being used directly for heating applications, the electrical energy generation potential will have to be reviewed as the fuel supply is now being divided between the two applications.

Output of the process (digestate as bio-fertiliser)

The anaerobic conditions in the digestion tank ensures the destruction of all major pathogens such as *E-coli*, *Salmonella and Campylobacter* making the slurry safe for any form of agricultural land application (Dennis and Burke 2001, Burton *et al.* 2009, Bond and Templeton 2011, Msibi 2015, SAGEN and SABIA 2016). The fermented biomass discharge (digestate) from the digester tank is in the form of a liquid mixture of dissolved and spent organic matter. The digestate passes through a separating process where it is then separated in solid bio-fertiliser matter (30 % to 35 % dry matter and liquid bio-fertiliser (1 % to 2 % dry matter). The thin mud-like slurry is pumped into a lagoon storage unit and can be applied onto farmland through an application system as a faded bio-fertiliser (Steyn 2017). The same quantity of material that is fed into the digester is also taken out of the tank at the same frequency as the loading rate. Chicken manure, fruit and vegetable discharge from the digester can immediately be pumped to the irrigation system or it can be stored in the pond for later distribution (Steyn 2017). The discharged from cow slurry is cooled in a one-day holding pond before it is distributed for land application on a daily basis (Steyn 2017).

Maintenance

The estimated plant life and discount period for on-farm CSTR digester designs is approximately 20 years. The mixer in the mixing pond as well as the slurry pump will require major maintenance or replacement after five years of operation. Maintenance on rotating machinery is required on years 5, 10, 15 and 20. Expected maintenance expenses are approximately 1 % every year and 6 % every five years respectively of the total plant cost (Steyn 2017). Generator maintenance interval should occur every 400/2000/8000 hours for general/medium/major services with expected life of 40 000 hours, i.e. 10 years for 12h/day operation. Re-conditioning overhaul is required on 40 000 hours (Steyn 2017).

On the gas handling system all the H_2S condensate traps should be checked and drained on a weekly basis. A total of 300 hours per year of generator down-time is required for routine maintenance of the generator engine. During the generator servicing/maintenance, the plant does not produce electricity except if the plant was constructed with generators in parallel configuration, but the digester continues to produce methane gas that can be flared off (Steyn 2017).

Development procedure

Before any biogas digester of any scale is constructed in South Africa, it is recommended that role definitions are identified and clarified before the project is underway (GreenCape 2017a). Table 1 illustrates the specific roles applicable in the process of the anaerobic value chain as guideline to construction. The phases (pre-development, development, construction and commissioning, operations and maintenance) are identified as being most relevant to the South African biogas industry (AltGen, GIZ, SAGEN and GreenCape 2014). For the purpose of biogas generation, pre-development and development are two separate phases; however, going forward in South Africa, these two phases should be combined under “development”.

The regular monitoring of a biogas plant where processes are evaluated to identify shortcomings and good performances as well as optimisation possibilities, is seen as the best way to towards sustainable biogas production. Awareness of each stage of the process and the possibilities for improvement is one of the most important steps towards optimal biogas production (Bachman 2015, Steyn 2017).

Table 1: The specific roles applicable in the process of the anaerobic value chain, with specific reference to the South African biogas industry (Source: AltGen, GIZ, SAGEN and GreenCape 2014).

Pre-development	**Development**	**Construction and commissioning**	**Operations and maintenance**
Site selection, Feedstock evaluation, Pre-environmental assessment, Preliminary plant design, Financial prefeasibility	Project management, Technical finalisation, Environmental impact assessment, Permitting and licensing, Bankability and project finance, Financial cost analyses	Procurement, Site and construction management, Commissioning, Performance testing	Operations management, Technical maintenance and monitoring, Feedstock supply and management, Output management (digestate), Trouble shooting

It is further important to remain attentive to the strengths and mistakes of other projects and to investigate new opportunities and possibilities for synergies. This process is continuous and requires committed, innovative and dynamic operational managers that are motivated to keep up with best practice and the latest technological developments (Bachman 2015, Steyn 2017).

APPENDIX H: Abbreviations

ABC - American Biogas Council

AD - Anaerobic digestion

AGET – African Green Energy Solutions

ASBR – Anaerobic Sequencing Batch Reactor

BD – Biogas Digster

BGK - Bundesgütegemeinschaft Kompost e.V. (Federal Association of Compost e.V.)

BMW - Bayerische Motoren Werke

BRICS – Brazil, Russia, India, China, South Africa

BSI PAS – British Standards Institution Publically Available Specification

CAGR - Compound Annual Growth Rate

CDM – Clean Development Mechanism

CEA – Clean Energy Africa

CER – Certified Emissions Reduction

CEPa – Combined Economic Potential

CEPb – Combined Environmental Potential

CFST – Continuous-flow Stirred Tank

CHP - Combined Heat and Power

CMF – Completely Mixed Flow Reactor

CPUT - Cape Peninsula University of Technology, South Africa

CSP – Combined Social Potential

CSTR – Continuously Stirred Tank Reactor

DA –Department of Agriculture

DAFF – Department of Agriculture, Fisheries and Forestry

DALY - Disability-Adjusted Life Years

DBSA - Development Bank South Africa

DEA – Department of Environmental Affair

DEA&DP – Environmental Affairs and Development Planning

DEDAT – Department of Economic Development and Tourism

DH – Department of Health

DIY – Do It Yourself

DM – Dry Matter

DNT – Department of National Treasury

DoE - Department of Energy

DTI - Department of Trade and Industry

DST - Department of Science and technology

EBA – European Biogas Association

EEG - Renewable Energy Sources Act, Germany

EIA - Environmental Impact Assessment

EPI – Environmental Performance Index

ESI-AFRICA - Electricity Supply Industry, AFRICA

ESI – Environmental Sustainability Index

ESKOM - state-owned vertically-integrated electricity company

EU – European Union

FAO - Food and Agriculture Organization of the United Nations

FERTASA – Fertiliser Society of South Africa

FEW - Food Energy Water

FS – Free State (South African province)

GBA – German Biogas Association

GDP – Gross Domestic Product

GEEF - Green Energy Efficiency Fund

GHG - Greenhouse Gas

GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit (German Society for International Cooperation)

GPAER - Green Peace Advanced Energy Revolution

HRT – Hydraulic Retention Time

IBR – Induced Blanket Reactor

IDC - Industrial Development Corporation

IDM - Eskom Industrial Demand Side Management

IDM- Eskom Integrated Demand Management

IPPs - Independent Power Producers

IRP - Integrated Resource Plan for electricity

ISSF - International Stainless Steel Forum

KZN – Kwa-Zulu Natal (South Africa province)

LFG – Landfill Gas

LGM – Long Gap Mill

LPG – Liquefied Petroleum Gas

Ltd - Limited

MCEP - Manufacturing Competitiveness Enhancement Programme

MDGs - Millennium Development Goals

MFMA - Municipal Finance Management Act

MSA - Municipal Systems Act

MSW - Municipal Solid Waste

NDP - National Development Plan

NEM:WA – National Environmental Waste Act

NEMA - National Environmental Management Act

NEPAD - New Partnership for Africa's Development

NERSA - National Regulator of South Africa

NEW – Nutrient, Energy and Water

NFSD - National Framework for Sustainable Development

NGO - Non-Governmental Organization

NNFCC - The National Non-Food Crops Centre

NSSD - The National Strategy for Sustainable Development and Action Plan

NT – National Treasury of South Africa

NT-MFMA - National Treasury of South Africa Municipal Financing Management Act

NWMS - National Waste Management Strategy

OECD - Organisation for Economic Co-operation and Development

OM – Organic Matter

Pty – Proprietary Company (business structure under Australian and South African Law)

REIPPPP - Renewable Energy Independent Power Producer Procurement Programme

RES - Retail Electricity Suppliers

RSA – Republic of South Africa

SA – South Africa

SAAEA - South African Alternative Energy Association

SAB – South African Brewery

SABIA – Southern Africa Biogas Industry Association

SADC - Southern African Development Community

SADEC - Socioeconomic data and application centre

SAGEN - South African-German Energy Programme

SALGA – South African Local Government Association

SAPA – South African Poultry Association

SAIREC – South African International Renewable Energy Conference

SANEDI - South African National Energy Development Institute

SAOGA – South African Oil and Gas Alliance

SARETEC - The South African Renewable Energy Technology Centre

SC – Sustainability Category

SCF – Sustainability Category Factor

SDG – Sustainable Development Goals

SEPA - Scottish Environment Protection Agency

Sci. Tech. Co. Ltd - Science and Technology Company Limited.

SIR - Substrate Induced Respiration

SOM - Soil Organic Matter

SOP - Standard Offer Programme

SPC – Sustainability Potential Category

SPS - Sustainability Potential Score

SPSC – Sustainability Potential Score Category

SRT – Solid Retention Time

SSEG – Small-Scale Embedded generation

STATSSA – Statistics South Africa

S1 – Survey 1 (Farmers without biogas digesters)

S2 – Survey 2 (Farmers with biogas digesters)

TSPP – Total Sustainability Potential Percentage

TSPV – Total Sustainability Potential Value

UASB - Up-flow Sludge Blanket Digester

UFH – University of Fort Hare, South Africa

UN – United Nations

UNDP – United Nations Development Programme

UNEP – United Nations Environmental Programme

USAB – Upflow Anaerobic Sludge Blanket

USD - United states of America Dollar

USDA – United States Department of Agriculture

WC – Western Cape (South African Province)

WISA – Water Institute of Southern Africa

WISP – Western Cape Industrial Symbiosis Programme

WMFP- Waste Management Flagship Programme

WRC – Water Research Commission

WWF - World Wide Fund for Nature

WWF_ FEW - World Wide Fund for Nature Food Energy Water report

WWTW - Wastewater Treatment Works

ZAR – South African Rand