Antecedents of successful commercial biogas implementation in South Africa

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ABSTRACT

Despite its demonstrated ability to provide benefits to the user and the environment, the commercial dissemination of biogas in South Africa has been less favourably received than other renewable energy technologies which have advanced drastically over the last decade.

By means of literature review and interviews with key stakeholders in the biogas industry, this study sought to identify and understand the factors necessary for commercial biogas implementation in South Africa to succeed. The study focuses on the South African context, in contrast to other economic or technological-only analyses that have been done previously.

Enhancements to energy security and environmental security were found to be the most prominent enablers for biogas; mainly that biogas dissemination can help alleviate municipal, agricultural and industrial organic effluent load into the South African ecosystems. It is further emphasised that the continued sustainability and proper management of the environment is an important factor for economic progress and sustainability, and that biogas implementation can assist in achieving this.

Biogas has not been explicitly incorporated into commercial-scale energy and waste policies, nor has it received the necessary attention within the environmental incentives of the Republic of South Africa. The concurrent lack of enforcement of the existing waste management regulations results in alternatives for industries to dispose of organic waste in a cheaper and sometimes less responsible manner.

This study proposes that the value proposition of biogas in South Africa should be positioned primarily as a significant and effective organic waste abatement function instead of a tool for energy production, and that biogas should receive separate attention from a policy and incentives perspective.

DECLARATION

I, Albert Stefanus de Bondt, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Business Administration in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Albert Stefanus de Bondt

Signed at Parktown, Johannesburg

On the 23rd day of September 2018

DEDICATION

To my mother, Hanlie, who has always supported and inspired me.

ACKNOWLEDGEMENTS

I am grateful for the academic and administrative staff of Wits Business School staff for providing the enabling platform for this research.

I further extend my appreciation and gratitude to the respondents of this qualitative research, and to my research supervisor for his guidance during this process.

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LIST OF ABBREVIATIONS USED

Abbreviation	Description
AD	Anaerobic digestion
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
GHG	Greenhouse gases
IPP	Independent power producer
IRP	Integrated Resource Plan
kW	Kilowatt
MW	Megawatt
GW	Gigawatt
kWh	Kilowatt-hour
MLD	Megaliters per day (million litres per day)
NERSA	National Energy Regulator of South Africa
OECD	Organisation for Economic Co-operation and Development
REIPPPP (REI4P)	Renewable Energy Independent Power Producer Procurement Programme
WWTP	Wastewater treatment plant

CHAPTER 1. INTRODUCTION

1.1 Purpose of the study

The purpose of the study is to identify and understand the necessary factors that would allow the successful implementation of biogas on a commercial-scale in South Africa. The study intends to determine these factors using thorough literature review and rigorous qualitative research focussing on the topic in South African context.

1.2 Context of the study

While regarded by the World Economic Forum as the most advanced economy in Africa (World Economic Forum, 2015, 2016b), South Africa has seen the comparably slow uptake of renewable energy that is being observed internationally. Industrial growth and urbanisation of the population have placed increasing strain on South Africa's capacity for electricity supply, for example, the Eskom power crisis of 2008 (World Wide Fund for Nature, 2014) that arguably led to economic losses exceeding R20bn. Ineffective management of waste from agriculture, municipalities and industries have given rise to organic waste products accumulating in ecosystems leading to eutrophication and contamination of fresh water supplies such as Hartebeespoort dam and the Vaal River (Brent, 2014).

The White Paper on Renewable Energy (Republic of South Africa, 2003), published by Government in 2003, was the founding formalised initiator of the concepts sustainability and energy security in South Africa. The White Paper proposes the gradual introduction of renewable energy technologies into the fossil-fuel intensive energy mix and would result in increased energy security and simultaneously, environmental sustainability. The White Paper was followed by the Integrated Resource Plan (IRP) for electricity in 2010 which formalised allocations of renewable energy for electricity production into the National Grid (Republic of South Africa, 2013). In 2013, the formulation of the National

Development Plan (NDP) also supported the incorporation of renewable energy technologies into the energy mix (Republic of South Africa, 2011c).

Perhaps the most successful and industry-shaping policy was announced in 2011 – the auction-based tariff programme: REPPPP “REI4P”; this programme was a rigorous and transparent private sector-led bid for renewable energy projects; REI4P produced 3,920 MW worth of electricity generating capacity over 64 projects for South Africa between 2011 and 2013 (Republic of South Africa, 2015). 98.7% of the capacity prescribed by REI4P during bid rounds 1 – 4, was fulfilled by wind, solar photovoltaic and concentrated solar power, with the remainder being hydroelectric power and biomass (Republic of South Africa, 2015) .

However, a study by the CSIR in 2016 indicates that 88% of the electricity production is derived from coal resources (Council for Scientific and Industrial Research, 2016). South Africa’s reliance on fossil fuels, therefore, remains high, and places risk on its ability to provide a supply sufficiently diverse which would constitute energy security (International Energy Agency, 2016b). In 2017, South Africa ranked 76th out of the countries evaluated and was particularly penalised on energy self-sufficiency and diversity of supply (World Economic Forum, 2016a). The construction and commissioning completion of Eskom’s Kusile and Medupi coal-fired power stations in the foreseeable future is a further testament to the continuance of the trend of fossil-fuel reliance.

Furthermore, South Africa assented to the Kyoto Protocol in 2002 but has since not made appropriately significant progress in reducing its greenhouse gas emissions (World Wide Fund for Nature, 2014).

Concomitant with energy security concerns, South Africa faces long-term environmental challenges concerning water management, wastewater treatment and agricultural waste runoff into the water table. The Yale Center for Environmental Law & Policy based at Yale University, (Yale Center for Environmental Law & Policy, 2018) ranked South Africa number 142 out of 180 countries on its Environmental Performance Index (EPI). On this scale, South

Africa was penalised on the aspects of air pollution, climate and energy management, and most significantly on wastewater management and sanitation.

> "Wastewater is a critical component of the water cycle and needs to be managed across the entire water management cycle: from freshwater abstraction, treatment, distribution, use, collection and post-treatment to its reuse and ultimate return to the environment, where it replenishes the source for subsequent water abstractions." (United Nations World Water Assessment Programme, 2017, p. 17)

Considering South Africa's present circumstances and energy security aspirations, the field of bio-energy is the only type of renewable energy which could derive benefits from organic waste and by-products of existing agricultural and industrial processes. The dissemination of biogas – albeit in the REI4P programme and industry at large, has not enjoyed the same success as other renewable energy technologies. Commercial agriculture and industrial processes in South Africa produce significant organic waste products including those contained in water effluents, and their potential needs to be strongly considered.

1.3 Problem statement

1.3.1 *Main problem*

The main problem is that the specific requirements for successful commercial biogas implementation in South Africa are not fully understood.

1.3.2 *Sub-problems*

The first sub-problem is the identification and understanding of the factors that would enable commercial biogas implementation in South Africa.

The second sub-problem is the identification understanding of the factors that would inhibit commercial biogas implementation in South Africa.

1.4 Significance of the study

Amigun, Sigamoney, & von Blottnitz (2008) discuss how energy is a critical enabling factor for the development of countries in Africa and that the utilisation of identified potential is subject to overcoming specific barriers that exist on the continent.

As cited by Biswas et al. in Amigun, Musango, & Stafford (2011)

> "Africa suffers from two sets of problems: dependence on export products that are of declining importance in world trade and the loss of market share for primary exports… RE technologies (RETs) offer developing countries some prospect of self-reliant energy supplies at national and local levels, with potential economic, ecological, social, and security benefits." (2011, p. 695).

Amigun et al. (2011) compared biogas to other forms of renewable energy such as solar, wind, hydro, and other bioenergy options; their findings were that energy-to-biogas is one of the only types of energy that fulfils both an energy production and waste abatement function. Several other studies have demonstrated the potential for bio-energy (bioethanol, biodiesel and biogas) commercialisation in the Sub-Saharan Africa geographical region (Amigun et al., 2008; Amigun & Von Blottnitz, 2010; Rupf & De-Boer, 2015; Shane, Gheewala, Kasali, & Cob, 2015).

Concurrent with the importance of energy as an enabler for socio-economic development is the increasing importance of energy security, to which biogas can contribute materially (International Energy Agency, 2015).

An exploration of peer-reviewed academic research and corporate publications such as the International Energy Agency and the World Economic Forum, reveals vastly varying economic development plans, environmental legislation and technological capabilities amongst African countries. Often, for the sake of simplicity and collaboration of researchers, geographic or economic regions are grouped such as "Sub-Saharan Africa", "emerging markets", "Africa", and "Southern Africa", to name a few. The number of variables involved to consider are enormous and are subject to change as soon as the application of the research is sought in a particular country.

It is, therefore, useful to consider the topic of biogas in South Africa on a focused basis. This study aims to present the opportunity for focused examination of the enabling and inhibiting factors for biogas and aims to be relevant and practical. The author posits that bio-energy has an essential place in the future of the South African energy mix in respect of its potential energy security, environmental preservation and security, mitigation of greenhouse gases, waste abatement and water security abilities.

This type of inquiry intends to address aspects of biogas dissemination that would most likely have been overlooked if a cursory economic analysis of its viability were undertaken. The study intends to distil relevant literature from peer-reviewed journals, government policy documents and various corporate reports, into producing research that is heuristically and practically significant. It aims to meet the criteria of heuristic significance as described by Tracy (2010) and to provoke thought in a variety of audiences such as the renewable energy and agriculture sectors in South Africa.

1.5 Delimitations of the study

1.5.1 *Extendibility of conclusions*

The very purpose of this study is to examine the enablers and inhibitors of the subject within the specific South African context in present-day circumstances. Although the literature review may draw from international and local research, the results and conclusions of this study itself do not attempt to infer to Southern Africa, Sub-Saharan Africa, or other similarly categorised economies. It may, however, provide a potential basis for future research and recommendations in other geographic and economic regions.

1.5.2 *Technological considerations*

From a technology perspective, this study is limited to well-known and established methods of biogas production which utilise “standard” anaerobic digesters. This research does not technically explore advanced or frontier methods of production that may be available or those who may purport efficiency enhancements.

1.5.3 *The scale of biogas production and potential users*

Production of biogas as a product for commercial or “large-scale” users remain the focus of this study. Rural, subsistence and small-scale production are not directly explored because the author feels that these aspects serve a different purpose than large-scale implementation.

1.6 Assumptions

1.6.1 *Exclusion of energy crops*

This study excludes the growth of “energy crops” as a source of biomass and considers only waste or by-product biomass from agriculture, municipal and industrial sectors. This assumption is essential in the South African context because competition created by the use of energy crops threaten food security and the exploration of the topic of energy crops may detract from the intent of this study. Energy crops in respect of food security considerations are, however, briefly introduced in the literature review.

1.6.2 *Transferability and replicability of technology in South Africa*

Technology utilised in biogas production internationally is transferable to South Africa; this is a reasonable assumption because South Africa has a well-developed engineering skills base.

1.6.3 *Respondent responses*

The qualitative research methodology used in this study makes use of purposive non-probability sampling, where it shall be assumed that the respondents provide reasonable, normal perspectives and experiences that are not subject to bias.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The literature review is arranged into three discussion topics which aim to provide context to the research problem in a structured manner and to develop logical arguments leading to research propositions. Three topics of discussion are defined as follows:

1. ***Biogas***: introduces the concepts of biogas production, production methods and mechanisms, the characteristics, and the uses of biogas products. The primary source of information shall be derived from published peer-reviewed journals.
2. ***Commercial biogas implementation***: explores commercial implementation considerations to provide appropriate international perspectives and introduces the fundamental bases for the eventual applicability of biogas dissemination regarding energy security and environmental security.
3. ***Commercial biogas implementation in South Africa***: considers commercial biogas implementation in respect of South Africa within its current circumstances, incorporating concepts from the first and second topics. Literature emphasis is placed on historical and current publications by stakeholders in the industry and government.

In conclusion, the information presented in the three discussion topics is distilled into palatable research propositions that address the two sub-problems, which aim to form an appropriate, relevant, and credible basis for the envisaged qualitative enquiry.

2.2 Biogas

2.2.1 *Biogas production and characteristics*

Biogas is the primary raw product gas produced by the process of anaerobic digestion of organic substrates (Chynoweth, Owens, & Legrand, 2000; Ward, Hobbs, Holliman, & Jones, 2008). In anaerobic digestion, several biological processes including acidogenesis and methanogenesis take place in an environment devoid of light and oxygen, giving rise to biogas and digestate as products (Greben, Burke, & Szewczuk, 2008; Weiland, 2003). The figure below shows dome-shaped anaerobic digesters at a biogas plant.

Figure 2.1: Anaerobic digesters at a biogas plant (Shutterstock Images, 2018)

Feedstock for biogas production is known as biomass and can constitute any organic biological matter- waste or non-waste. Depending on the feedstock and process conditions, the composition of biogas varies mostly in respect of methane, carbon dioxide, carbon monoxide, and moisture, with small quantities of impurities (Chynoweth et al., 2000; Ryckebosch, Drouillon, & Vervaeren, 2011). Biogas technology was introduced into sub-Saharan Africa in the early 1950’s, where uptake has since been sporadic but extensive in countries such as Tanzania and Rwanda (Rupf & De-Boer, 2015). The promotion of the use of biogas in these countries has traditionally been geared towards smaller scale applications due to its relative simplicity for the rural subsistence user. The production of biogas is rudimentary *vis-a-vis* other bio-energy sources such as bioethanol and biodiesel; this is because biogas production does not require the addition of chemicals and does not rely on specific technology.

It is useful to place biogas as an energy source in the context of other forms of energy. The following graphic, compiled by the author of this study, represents a simplified summary of energy sources.

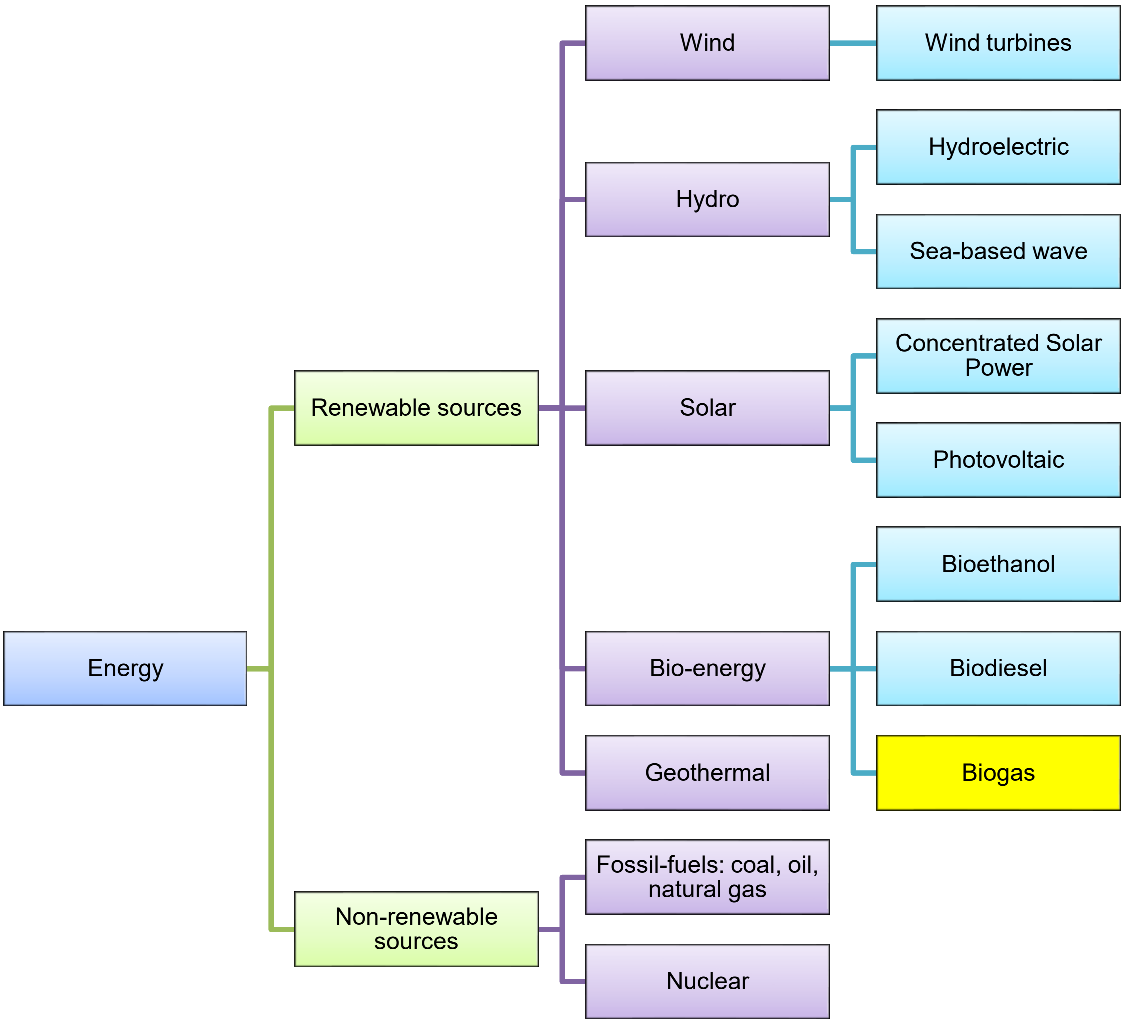

Figure 2.2: Biogas in context of the energy mix (researcher's summary)

Biogas can be categorised as *bio-energy*, amongst biodiesel and bioethanol; it is a renewable source of energy given that its feedstock is both organic and replenishable. Biogas is often referred to as biomethane after it has been purified (Ryckebosch et al., 2011). Bio-energy types also include other combustible energy source products which are produced from organic feedstocks.

The figure hereunder, depicts the standard products of anaerobic digestion and their constituents.

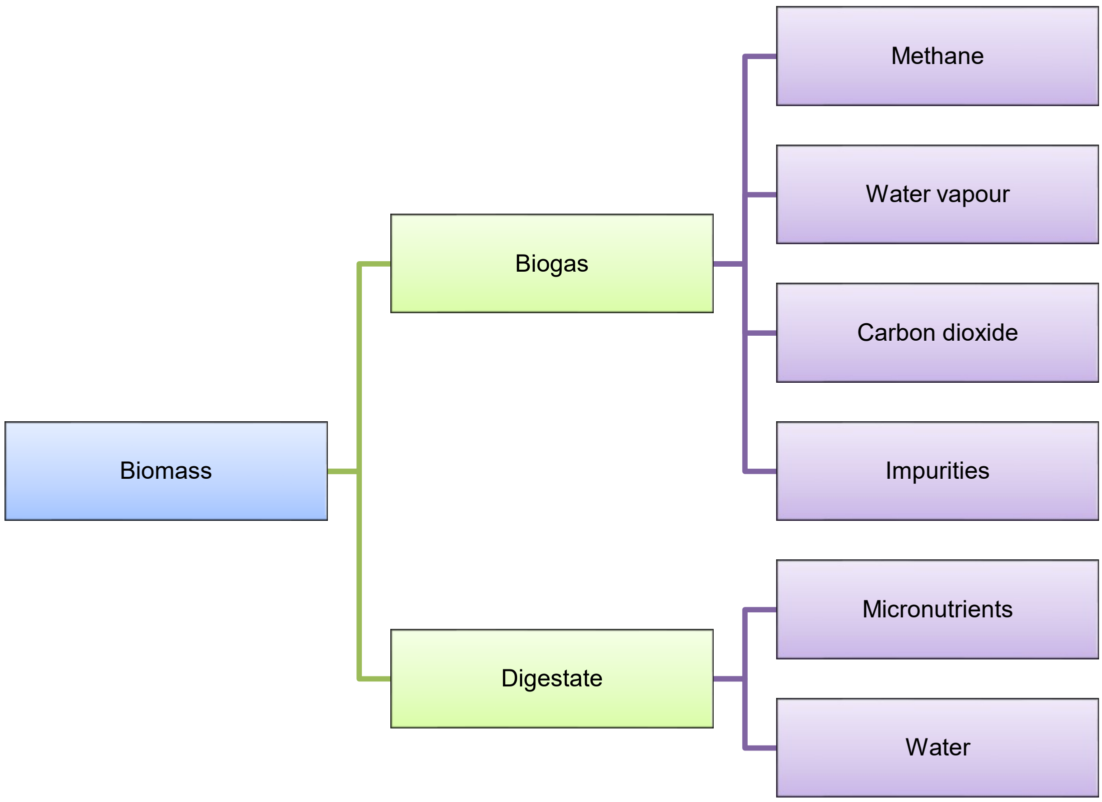

Figure 2.3: The overall biogas overall process (adapted from Appels et al.; Appels, Baeyens, Degrève, & Dewil; McKendry (2011; 2008; 2002b))

Digestate produced by the AD process is typically a consistent, nutrient-rich slurry or solid that is often used as a fertiliser in agricultural applications (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012). Biogas can be processed further in various ways, and its potential applications are presented in the following figure.

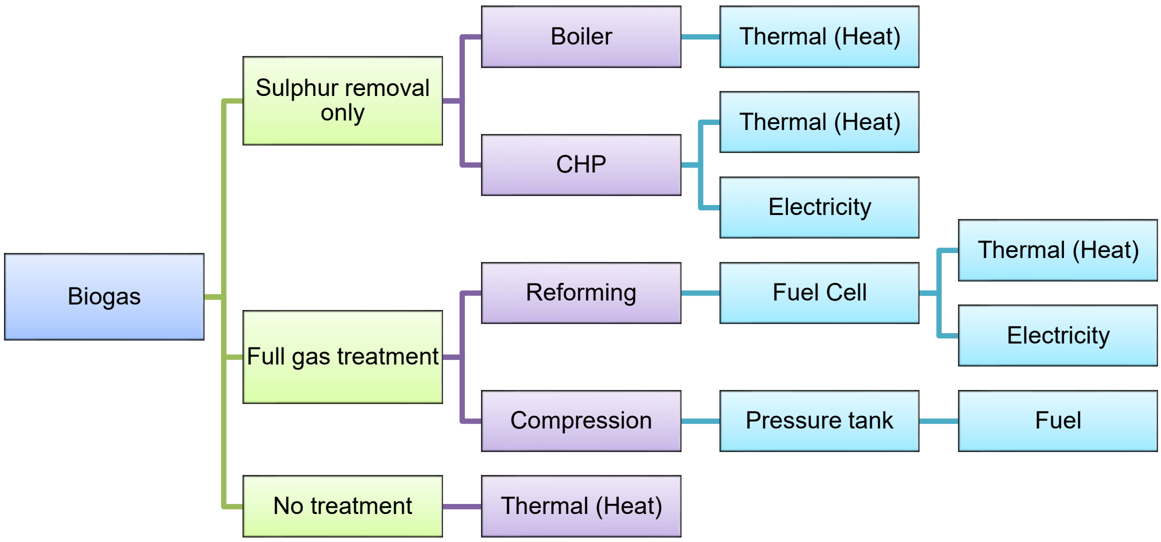

Figure 2.4: Potential uses for biogas (adapted from Appels et al. (2008))

As indicated, for uses other than heating the raw biogas may require desulphurisation (removal of sulphur compounds) and drying to prevent corrosion and damage to mechanical equipment such as boilers, CHP generators, and compressors (Appels et al., 2008).

Additionally, biogas is very similar to natural gas after it has been treated, and typically, heating apparatus can make use of biogas instead of liquefied petroleum gas (LPG) or natural gas, without requiring significant modifications (Ryckebosch et al., 2011; Weiland, 2010). The figure below depicts a modern biogas plant.

Figure 2.5: Modern biogas plant (Shutterstock Images, 2018)

2.2.2 *Digestate as organic fertiliser*

Agricultural activities often use manure and waste organic matter as a direct source of fertiliser for growing crops. Alburquerque, de la Fuente, Ferrer-Costa, et al., and Bernal, Alburquerque, & Moral (2012; 2009) compared the efficacy of untreated biomass (such as manure) used as a fertiliser, against the same biomass which had passed through an anaerobic digester. Their studies found more beneficial effects of the digestate as compared with non-digested biomass only and cite increased levels of nitrogen and phosphorous (produced by the bacteria in the process) as some of the reasons for the soil quality improvement. Their studies also found elevated microbial and enzyme activity in the soil, which are favourable conditions for agriculture (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012).

2.2.3 *Feedstock types*

Collectively, the feedstock or combination of feedstocks used to produce biogas is known as biomass. Since a multitude of biomass is produced in agriculture and industry, it is useful to categorise them into four major types, after McKendry (2002a):

1. Woody plants;
2. Herbaceous plants and grasses;
3. Aquatic plants;
4. Animal manure.

Alternatively, Acaroglu, Kocar, & Hepbasli and Siemons (2005; 2002) categorise biomass according to their source as follows:

1. Residues – agricultural, forestry, and industrial;
2. Wastes consisting of or containing biomass such as municipal waste, industrial waste, landfill gas, and sludge gas;
3. Energy crops.

Sources of plant-based biomass can be categorised into two groups based on their agricultural purpose. Firstly, as energy crops – those specifically grown to produce a biomass feedstock; secondly, as residues or wastes – those secondary or by-products that arise during the ordinary course of production of plant-based crops for food production (Gebreegziabher, Naik, Melamu, & Balana, 2014; Saladini et al., 2016). Cattle, pig, and chicken manure, for example, are also residues of regular production that constitute useful biomass.

Current use in South Africa for many (but not all) of the waste residues include direct use of animal manure as fertiliser for growing crops in agriculture, and crop cuttings being mixed with feed for cattle. Unfortunately, a significant amount of waste residue biomass is not currently utilised (Republic of South Africa, 2003).

Anaerobic digesters can receive virtually any organic substrate as a feedstock. Its localised production offers an attractive value proposition for using residue biomass to produce biogas for energy, and digestate as fertiliser (Alburquerque, de la Fuente, Campoy, et al., 2012; Bernal et al., 2009; Ward et al., 2008).

Integrated industrial or agricultural regions may derive significant benefit by combining their biomass at a central, localised site, and distribute the power between themselves – either as selling the electricity to one another and sharing the capital costs or selling the power directly back into the grid to derive a sort of rebate benefit.

2.2.4 *Co-digestion of feedstocks*

Co-digestion refers to the act of combining different types of biomass such as animal manure and maize silage to feed anaerobic digestion processes (Weiland, 2010). Many producers choose to beneficially integrate different biomass feedstock into one anaerobic digester (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012), where the technique has been shown to produce higher biogas yields than with a single type of feed only. Studies have also demonstrated these techniques as having a more sustainable positioning regarding life cycle analysis (Alburquerque, de la Fuente, Ferrer-Costa, et al., 2012; Boulamanti, Donida Maglio, Giuntoli, & Agostini, 2013; Ward et al., 2008).

2.2.5 *Wastewater treatment*

Municipal wastewater treatment processes use anaerobic digestion techniques as a part of the treatment process, but the biogas that is produced is often not captured at all, nor integrated efficiently (Stafford, Cohen, Hille, Harrison, & Burton, 2013). In developing countries where municipal wastewater treatment facilities are often antiquated or not maintained, the biogas by-product is vented to the atmosphere, and additional electricity imported along with fossil-fuel energy burnt for wastewater energy requirements (Bani Shahabadi, Yerushalmi, & Haghighat, 2009).

Wastewaters are a viable feedstock for biogas production process in that they possess elevated levels of organic material, mostly in a dissolved form, giving rise to high levels of chemical oxygen demand (Agricultural Research Council, 2016). Agricultural activities from animal husbandry and blackwater generate wastewater, and significant volumes of industrial wastewater are produced from distilleries, breweries, fruit pulpers, paper and petrochemical industries.

Kamali, Gameiro, Costa, & Capela (2016) investigated the anaerobic digestion of industrial pulp and paper mill wastes and found that it could provide the benefits of biogas production and additionally, GHG abatement. Typical industrial wastewater effluent is shown below.

Figure 2.6: Industrial wastewater effluent (Shutterstock Images, 2018)

2.2.6 *Odour and pathogen mitigation*

Further benefits of the use of the anaerobic digestion of residue biomass such as animal manure and other slurries include the reduction of odours and the reduction of pathogens (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009).

2.2.7 *Environmental impacts*

Intensified animal production in countries producing surplus animal-based manure results in an adverse impact on the environment insofar as GHG emissions and untreated organic wastes are concerned (Holm-Nielsen et al., 2009). Jorgenson (2006) discusses the effects and potency of methane as a GHG as compared to the well-known carbon dioxide, citing that methane is at least ten times more effective than carbon dioxide in its ability to reabsorb and radiate infrared energy back to earth.

According to findings by Boulamanti et al. (2013), two leading factors influence the sustainability and potential GHG savings obtained from anaerobic digestion; firstly the choice of feedstock: energy crops are known to produce higher yields, but their cultivation effect and transportation were considered to negate these effects. Secondly, their findings indicate that the handling of the digestate produced is significant in that closed storage tanks and rapid use of the digestate as fertiliser offsets the emissions that would be caused by fertiliser production.

Studies have suggested that brewery wastewater could be beneficial in improving water balance and environmental footprint (Agricultural Research Council, 2016; Bocher, Agler, Garcia, Beers, & Angenent, 2008; Parawira, Kudita, Nyandoroh, & Zvauya, 2005; Poh, Gouwanda, Mohan, Gopalai, & Tan, 2016; Stafford et al., 2013).

2.3 Commercial biogas implementation

2.3.1 *Commercial and non-commercial scale*

Most modern research in the African context focuses on biogas produced for non-commercial means where rural communities would derive benefit from the products (Amigun & Von Blottnitz, 2010; Arthur, Baidoo, & Antwi, 2011; Nzila et al., 2012; Rupf & De-Boer, 2015; Southern African Biogas Industry Association, 2015).

In an attempt to define a commercial biogas plant Poeschl, Ward, & Owende, (2012) defines those facilities producing more than 500 kW of electrical power as commercial and small-scale biogas plants as those producing less than 500 kW.

The definition used by Poeschl et al. (2012) shall be considered a guide for the distinguishment during this study. Specific contextual uses of biogas where the differentiation needs to be made between commercial and rural, however, needs to rest on contextual factors such as the feed source (whether agricultural or subsistence) and the quantum of product produced – whether commercial benefit could be derived or not.

Within the context of a proven growing biogas market in sub-Saharan Africa (Amigun et al., 2011, 2008), this study also considers production processes from which relatively significant economic benefit could be derived and is therefore not strictly limited to 500 kW as suggested.

2.3.2 *Energy security*

Over the past decade, a clear increasing trend has emerged where governments and non-governmental organisations in global markets are focusing on energy security (International Energy Agency, 2016b). The concept of "energy security" emerged in the 1970's, where significant events such as the OPEC oil embargoes and the Iranian Revolution impacted world oil supply (World Economic Forum, 2016a). Given that in the 1970's the world's reliance on oil as one of the only energy sources was more significant than it is today, energy security has received much more attention.

As cited by World Economic Forum (2016a), the Asia Pacific Energy Centre (2007) attributes "the four A's" to help define energy security, as follows:

1. Availability;
2. Accessibility;
3. Affordability;
4. Acceptability.

The World Economic Forum reports a quantitative measure of energy security of each country evaluated using the Energy Architecture Performance Index (EAPI). EAPI rankings consider the following attributes of energy security in a particular state:

1. Self-sufficiency and diversity of supply;
2. International security and geopolitical risks;
3. Infrastructure resilience and flexibility;
4. Economic risks and increases in demand;
5. Level and quality of access;
6. Governance and emergency response mechanisms.

The following figure depicts a global view of “Energy Access and Security” as reported by (World Economic Forum, 2017):

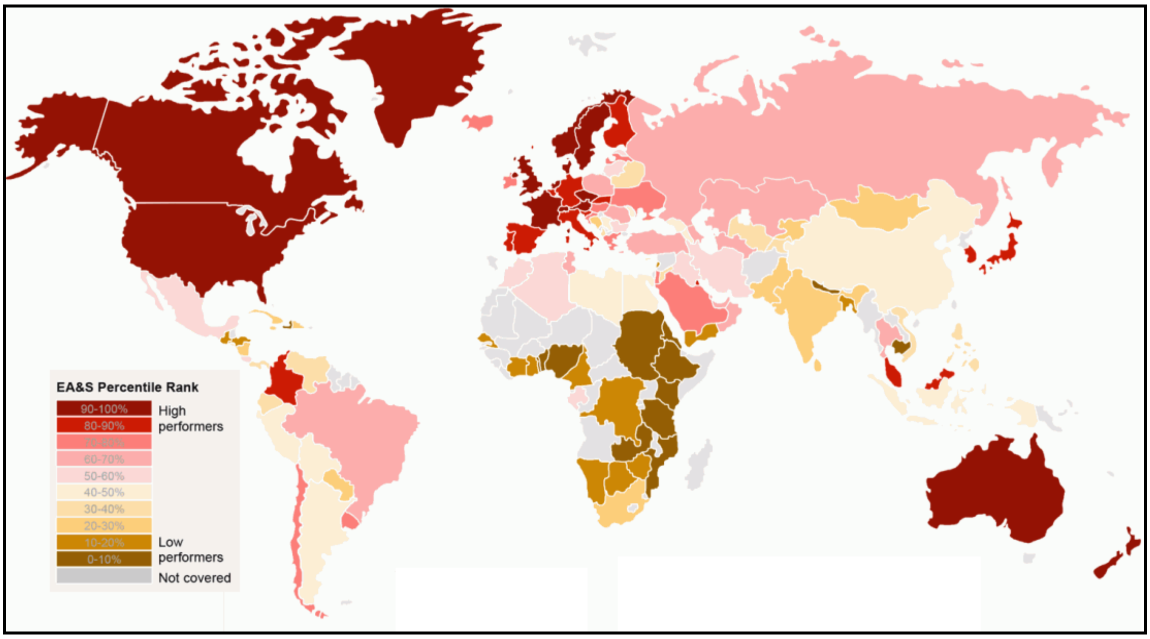

Figure 2.7: WEF EA&S percentile rank map (World Economic Forum, 2017)

For comparative purposes, the energy security rankings for selected countries as per the 2017 index, are given below, noting that South Africa is placed at number 76.

Table 2-1: WEF Energy Security Rankings (World Economic Forum, 2017)

Rank	Country	Economy Category
1	Switzerland	Advanced economy
2	Norway	Advanced economy
3	Sweden	Advanced economy
8	Columbia	Latin America and Caribbean
17	Latvia	Emerging and developing Europe
36	Azerbaijan	Commonwealth of Independent States
50	Indonesia	Emerging and developing Asia
52	United States	Advanced economy
54	Republic of Congo	Sub-Saharan Africa
76	**South Africa**	**Sub-Saharan Africa**
95	China	Emerging and developing Asia

Energy security is coupled with the diversification of energy sources utilised; for example, developing countries that traditionally rely on fossil fuels have a relatively low energy security score (International Energy Agency, 2016b) because fossil fuels are exhaustible, non-renewable, create pollutants in the environment and are exposed to ever-increasing costs. Coal mining, for example, is relatively energy intensive in its primary and secondary processing and subject to increasing electricity costs and labour costs in growing markets (U.S. Department of Energy, 1990).

Notwithstanding the direct cost considerations of continued reliance on fossil fuels, there are significant indirect costs associated with fossil-fuel beneficiation and utilisation. These factors are greenhouse gas emissions, environmental damage to air, aquatic and land-based flora and fauna, and most notably, pollutants that may damage human health (Frankfurt School-UNEP Centre/BNEF, 2016).

2.3.3 *Environmental security*

The *Yale Center for Environmental Law & Policy* based at Yale University produces an annual environmental performance index which is a quantitative measure that incorporates 24 indicators into 10 issue categories and two policy objectives (Yale Center for Environmental Law & Policy, 2018). The weighting system is depicted in Appendix B for reference.

South Africa ranked 142 out of 180 countries on the Yale EPI scale for 2018 and performed particularly poorly on the aspects of air pollution and water quality – specifically wastewater treatment. The impacts from various sources of water contamination are succinctly depicted in the following figure.

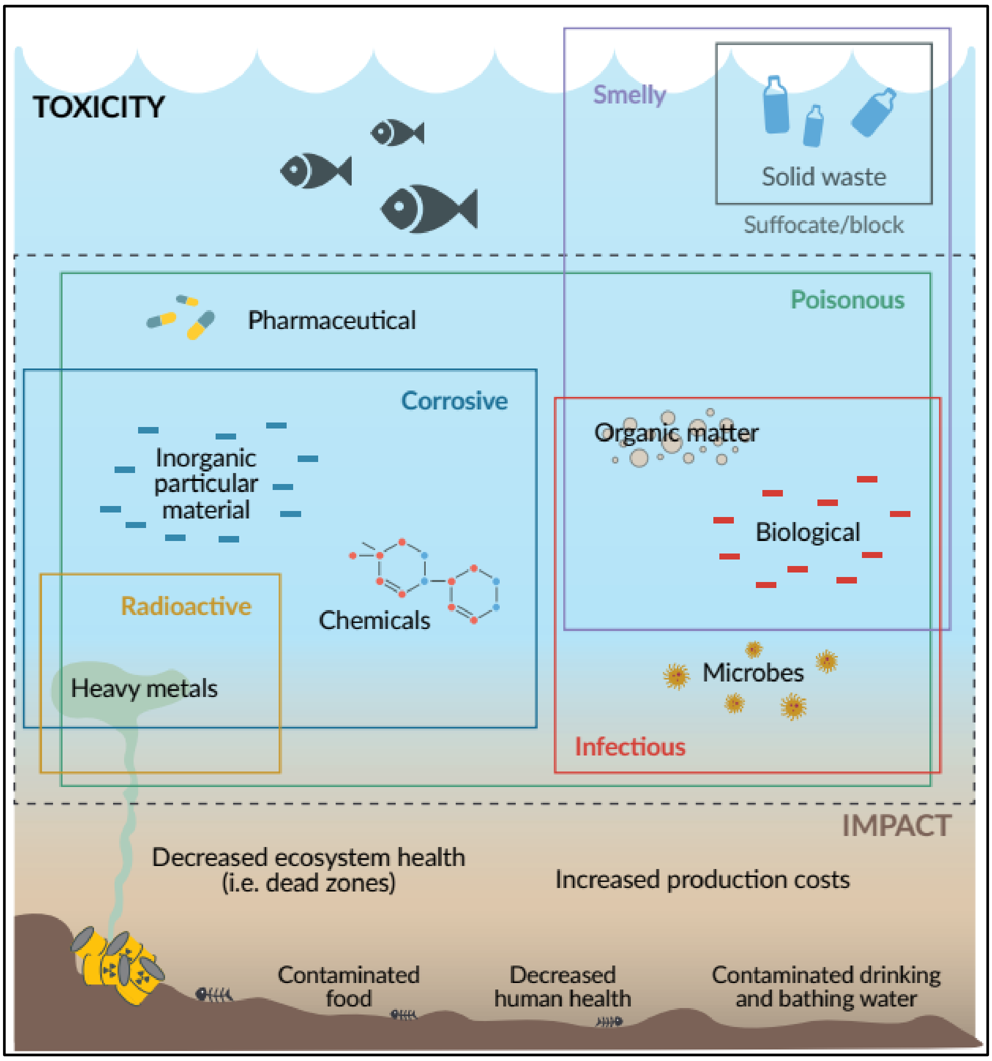

Figure 2.8: Water pollutant toxicity and impact summary (United Nations World Water Assessment Programme, 2017)

In particular, inadequate water system and waste management has detrimental impacts on ecosystem health, contamination of food and potable water, decreased human health and potentially increased production costs to purify or treat water for use.

Metric	Rank	Score
Water Resources	50,0	87,8
Biodiversity and Habitat	117,0	64,2
Fisheries	54,0	59,2
Heavy Metals	84,0	53,2
Agriculture	31,0	47,8
Climate and Energy	122,0	44,6
Air Quality	166,0	41,1
Air Pollution	133,0	34,7
Water and Sanitation	133,0	24,7
Forests	136,0	0,0

Figure 2.9: 2018 Yale EPI scores for South Africa (Yale Center for Environmental Law & Policy, 2018)

2.3.4 *Significant international producers*

Current commercial or large-scale biogas producers at the time of publication of this study have been obtained from case studies in academic literature and agencies such as the International Energy Agency who have a direct interest in energy from biological sources.

In 2014, world electricity production from fossil-fuels amounted to 15,885,302 GWh, where China produced 4,279,040 GWh from fossil fuels (International Energy Agency, 2016a), which represents 26.9% of the world's fossil fuel electricity production. In the same year, world electricity production from biofuels and waste was 492,848 GWh with China producing 57,489 GWh electricity from biofuels and waste (International Energy Agency, 2016c). This makes China one of the world's largest consumers of fossil fuels for electricity but also a substantial producer of 11.7% of world electricity production from biofuels and waste.

Jiang, Sommer, & Christensen (2011) review the biogas industry in China and identify that by the end of 2009, China had a total of 56,856 biogas plants, of which 3,939 are classified as large-scale making use of industrial organic waste and agricultural waste. Another 18,853 medium scale plants are making use of agricultural waste. The authors identify strong government policy on renewable energy as being supportive, but that poor implementation in the quality of the biogas plants and the lack of education of the operators running the facilities led to decreased efficiency.

According to a study by Lajda, Lajdová, & Bielik (2015) on the impact of biogas plants in Slovakia, that country alone has in operation more than 100 significant biogas plants. Lajda et al. (2015) further examined the link between the growth of the biogas sector and subsidy policy in Slovakia between 2009 and 2014 and reported a favourable correlation.

Weiland (2010) identified that in 2009, Germany became the most significant commercial-scale producer of biogas in the world, citing the more than 4,000 biogas plants operating in the agricultural sector on farms, and an average size of 500 kW_e (Poeschl et al., 2012). Weiland (2010) further discusses the successful injection of upgraded biogas into the existing natural gas reticulation grid in Germany, Sweden, and Switzerland; however, noting that the upgraded gas needs have a methane content of 95% (compared to the raw biogas product of approximately 50%). The image below shows a large biogas plant in Germany.

Figure 2.10: Commercial biogas installation in Germany (Shutterstock Images, 2018)

2.3.5 *Efficiency considerations*

Ward et al. (2008) explored the optimisation of the anaerobic digestion of agricultural wastes and suggested that most large-scale anaerobic digestion processes run at well below their capacity. Ward et al. (2008) propose various improvements on fundamental anaerobic digestion processes and highlights that in the European context, where the biogas industry is maturing, economic returns can be optimised by improving the biogas production technology leading to higher raw yields per tonne of feedstock.

2.3.6 *Food security*

Energy crops grown for energy production affects the concept of food security, which is discussed in the assumptions of this research, however, for context food security concerning biogas is mentioned here.

The source of biomass feedstock holds particular significance in developing countries that are producers of primary crops for export where the contribution of the agriculture industry to the gross domestic product (economy output) of the nation is essential (Council for Scientific and Industrial Research, 2014; International Energy Agency, 2017; Southern African Biogas Industry Association, 2015).

A net exporter of food crops such as Brazil produces so much sugar cane, for example, that it firstly dominates the market regarding supply-demand curve, and secondly, the surplus is used as biomass for Brazil's bioethanol blending scheme. The success of Brazil's agriculture is not shared by South Africa, for example, where poverty, drought and inflationary pressures constrain the biomass supply such that energy crops would compete with crops for food (Agricultural Research Council, 2016; Republic of South Africa, 2003, 2011b).

2.3.7 *Perspectives on financing and incentivisation*

For any infrastructure development to be possible, financing needs to be available and supported in that particular framework – whether the source of funds arises from government coffers funded by taxpayers, or loans from the World Bank or other corporate institutions that see potential in the investment.

It is logical that there exist specific factors which would persuade or discourage investors to contribute to energy infrastructure projects, and of particular interest, renewable energy, also known as cleantech. Bürer & Wüstenhagen (2009) conducted a detailed enquiry into the perspectives of international cleantech investors of renewable energy policy where they state the following:

> "Obviously, most venture capital and private equity investors are not political scientists, so their preferences should not be considered as perfect substitutes for scientifically grounded policymaking. Nevertheless, as investors are an important target audience for policymakers and their investment decisions have an important impact on markets, it is worthwhile studying their view about which policies work. Venture capital and private equity investors are particularly important to the innovation chain as they

> provide the early stage financing needed for new ventures to launch new clean energy innovations onto the market." (Bürer & Wüstenhagen, 2009, pp. 5004–5005).

Bürer & Wüstenhagen (2009) explored investor preferences for market-push and market-pull policies in respect of clean technology; the critical findings of the study indicate that supportive policy environments and policies such as feed-in-tariffs are enablers for investment in clean technology, but that policy alone is often not enough.

Globally, in countries that have successfully adopted and implemented renewable energy projects, various mechanisms have been used by governments and energy utilities to incentivise investment into large-scale renewable energy projects. Abolhosseini & Heshmati (2014) explored central support mechanisms for finance of renewable energy development, such as feed-in-tariffs. The Clean Development Mechanism is another concept and virtually a buzzword (Academy of Science of South Africa, 2014; Amigun et al., 2008; Baker, Newell, & Phillips, 2014; Rupf & De-Boer, 2015).

2.3.8 *Global initiatives contributing to the uptake of renewable energy*

The adoption of bio-energy related technologies and implementations into energy infrastructures of countries globally would fall under the umbrella of renewables. Bürer & Wüstenhagen (2009) described market-push and market-pull phenomena. Since the inception of the well-known Kyoto Protocol in (United Nations Framework Conference on Climate Change, 1997), awareness of renewable energy and "clean" energy has increased, evidenced by the prominent emergence of corporate initiatives and non-profit initiatives which support renewables. Biogas production is discussed by Ravindranath, Balachandra, Dasappa, & Usha Rao (2006) and promoted as a means for potential greenhouse gas abatement.

2.4 Commercial biogas implementation in South Africa

2.4.1 *Renewable energy policy in South Africa*

In 2003, the Department of Minerals and Energy officially published its first intention to adopt renewable energy into South Africa's energy mix in a paper entitled "The White Paper on Renewable Energy". The government sets a target of 10,000 GWh M*toe* (million tons of oil equivalent) (Republic of South Africa, 2003):

> "10 000 GWh (0.8 Mtoe) renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and bio-fuels. This is approximately 4% (1,667 MW) of the projected electricity demand for 2013 (41,539 MW). This is equivalent to replacing two (2x 660 MW) units of Eskom's combined coal fired power stations." (Republic of South Africa, 2003, p. 25)

Against the backdrop of renewable energy, the paper discusses South Africa's reliance on fossil-fuels, GHG emissions, and sustainability. Its position on energy security, which was discussed in a preceding section of this study, refers to a statement made by the Department of Energy in 1998:

> "Given increased opportunities for energy trade, particularly within the Southern African region, Government will pursue energy security by encouraging diversity of both supply sources and primary energy carriers (DME, 1998)." (Republic of South Africa, 2003, p. viii)

The White Paper on Renewable Energy was succeeded by the IRP – Integrated Resource Planning for Electricity (Republic of South Africa, 2013).

Additionally, South Africa acceded to the Kyoto protocol in March 2002 (United Nations Framework Conference on Climate Change, 2010), where it was identified at the time to be a significant GHG emitter due to its dependence on coal.

Amigun et al. (2011) considers South Africa to be a technologically advanced developing economy and classifies risks technical, information and capacity as low rated hurdles, while institutional / policy, economic and financial hurdles are listed as medium-rated. The Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) was established to provide approximately 18 GW of electrical power from renewable sources by 2030 (Walwyn & Brent, 2015).

The table below presents the author's summary of the relevant government publications regarding renewable energy and bio-energy.

Table 2-2: Summary of South African renewable energy policies (researcher's summary)

Year	Publication Name
2003	White Paper on Renewable Energy
2009	Renewable Energy Feed-in Tariff
2009	Integrated Resource Electricity Plan 2010 – 2030 (IRP)
2011	Renewable Energy Independent Power Producer Procurement Programme (REIPPPP)
2011	Green Economy Accord
2012	National Development Plan 2030 (NDP)

The Green Economy Accord, as part of Government's New Growth Path, mentions vital aspects of a green economy such as renewable energy, energy efficiency, waste recycling, re-use and recovery, biofuels, reduction of carbon emissions (Republic of South Africa, 2011a). It does not, however, mention biogas potential.

2.4.2 *Legislation and regulation of waste in South Africa*

The following table provides the author's summary of selected Acts of Parliament of the Republic of South Africa, which apply to waste and concerns the topic of organic waste management.

Table 2-3: Summary of South African legislation concerning waste (researcher's summary)

Year	Publication Name
1947	Act No.36 of 1947: Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act, 1947
1973	Act No.15 of 1973: Hazardous Substances Act, 1973
1989	Act No.73 of 1989: Environment Conservation Act, 1989
1998	Act No.107 of 1998: National Environmental Management Act, 1998
1998	Act No.117 of 1998: Local Government: Municipal Structures Act, 1998
1998	Act No.36 of 1998: National Water Act, 1998
2000	Act No.32 of 2000: Local Government: Municipal Systems Act, 2000
2002	National Guidelines for Integrated Management of Agricultural Water Use: National Department of Agriculture
2004	Act No. 9 of 2004: National Environment Management: Air Quality Act, 2004
2008	Act No.59 of 2008: National Environmental Management: Waste Act, 2008
2009	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 National Policy on Thermal Treatment of General and Hazardous Waste (July 2009)
2010	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 National Waste Information Regulations (July 2010)
2012	Municipal Solid Waste Tariff Strategy (May 2012)
2013	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 List of waste management activities that have, or are likely to have, a detrimental effect on the environment (November 2013)
2013	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 Waste classification and management regulations (August 2013)
2013	The National Organic Waste Composting Strategy (April 2013)
2014	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 Draft National Norms and Standards for Organic Waste Composting (February 2014)
2016	Act No.59 of 2008: National Environmental Management: Waste Act, 2008 National Pricing Strategy for Waste Management (August 2016)

The act which appears to be the cornerstone for waste management of all kinds in South Africa today is Act No. 107 of 1998: National Environmental Management Act, otherwise known as NEMA. Government published a guide to understanding the Waste Act of the NEMA, and the following figure depicts the overarching guidelines (Republic of South Africa, 2012):

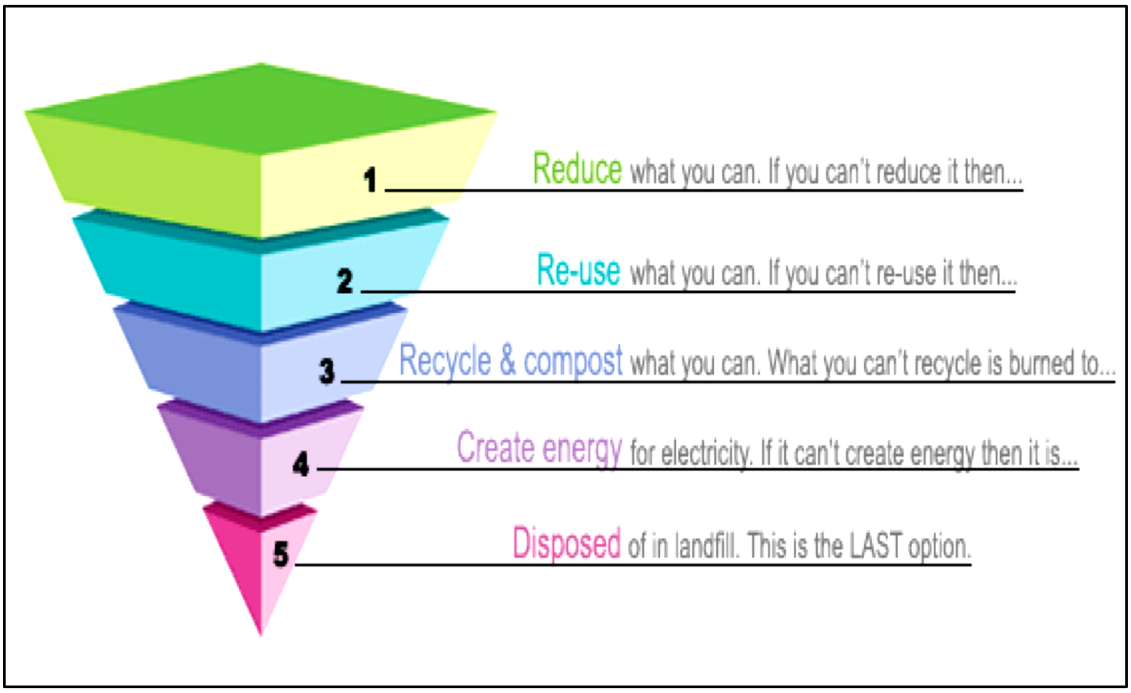

Figure 2.11: Hierarchy of waste management (Republic of South Africa, 2009)

The primary purpose of the Waste Act was to put into place law regulating the management of waste which would protect the health of people and the health of the environment.

There are provisions for landfill gas recovery in the Waste Act, but not specifically for biogas or AD. Biogas is mentioned in the Draft National Norms and Standards for Organic Waste Composting but more as a product of natural anaerobic digestions and not specifically biogas plant.

2.4.3 *Role players: private and public industry*

For this study, it is useful to classify two sectors in the South African economy; those who are part of the public sector in delivering services and those in the private sector, which may deliver services but whose primary aim is for profit.

Service delivery includes factors such as electricity supply, potable water supply and reticulation, sanitation and waste removal. In urbanised metropolitan areas, in particular, the infrastructure for landfilling of domestic and industrial waste, and wastewater treatment already exists. The infrastructure typically includes sanitation and sewage services which are centralised to local regions.

Privately owned (non-parastatals) industries, which are involved in refining processes, beer production and distilleries produce wastewaters that are known to have organic content in dissolved form. The organic constituents increase the chemical oxygen demand of the waters substantially and need to be treated by relevant statutory standards before being released into the environment.

It is noteworthy that the Department of Energy identified and successfully facilitated the REI4P which yielded to date some 3,920 MW of renewable energy using power purchasing agreements with the state-owned Eskom (Rycroft, 2013). Participants of the REI4P were private enterprises only.

According to SABIA (2017), SABMiller in Stellenbosch at their brewery treat some 4.5 million litres of wastewater per day using anaerobic digestion processes. Similarly, Distell in Stellenbosch treats approximately 1.5 million litres of wastewater per day. The benefits derived purport to be significant in that the wastewater treatment costs are abated, and the biogas produced by the process contained and utilised as boiler feed gas, which would otherwise have been serviced by either natural gas or coal.

2.4.4 *The potential positioning of biogas in South Africa*

The United Nations World Water Assessment Programme (2017) classifies the typical effluent content of primary industries containing significant levels of BOD, COD, and suspended solids as those industries including pulp and paper, food industry, brewing, dairy, textiles – all of which are prominent industries in South Africa.

A graphic reproduced by United Nations World Water Assessment Programme (2017) depicted below, shows the trend in BOD concentrations in rivers between 1990-1992 and 2008-2010.

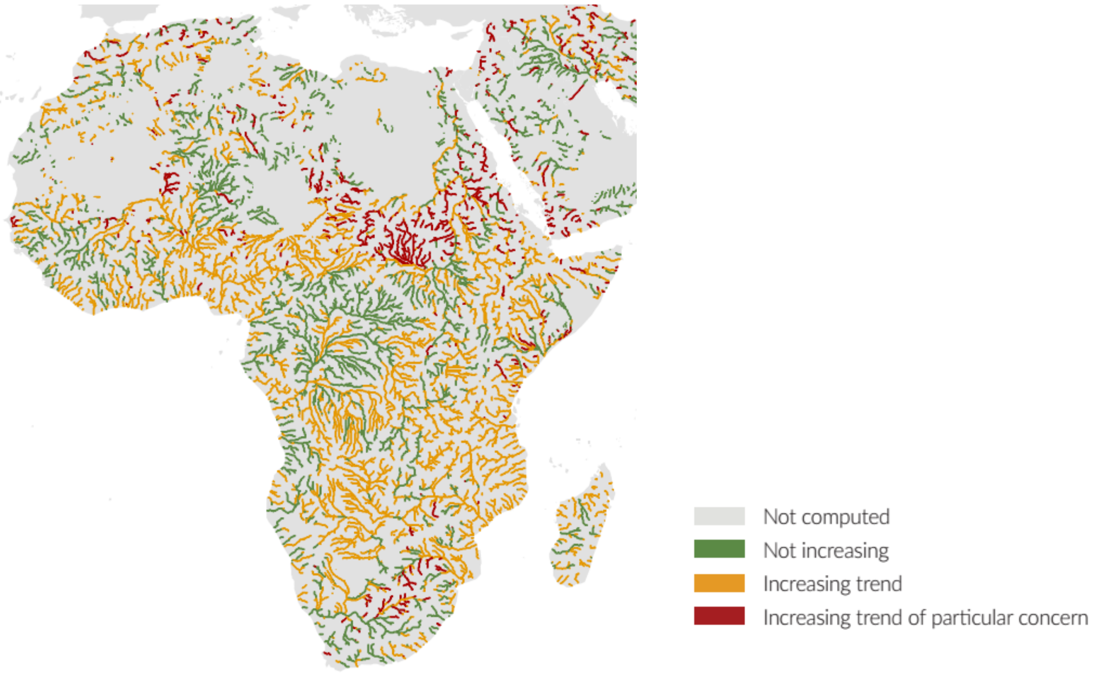

Figure 2.12: BOD concentration trend in rivers (United Nations World Water Assessment Programme, 2017)

According to the figure, the increasing trend of particular concern is apparent in South African rivers as well as increasing trends in general with many of the rivers over the continent. The sources of BOD as discussed in Section 2.3, are industries which emit unacceptable levels of organic components into the rivers, representing inadequate water emission management.

South Africa has some of the continent's largest paper and sugar mills, being owned by Illovo Sugar Limited, Mondi Limited, RCL Foods (formerly TSB Sugar). Illovo Sugar, for example, utilises bagasse, which the term is given to the cane cutting waste that is processed when milling the sugar cane.

Sugar mills burn the bagasse as a source of heat and utilise rudimentary, yet effective means of electricity production; in this manner, the Illovo Group (now owned by Associated British Foods) produces over 90% of their electricity (Associated British Foods plc, 2017). However, further potential exists where the sugar mills employ ash dams also known as sedimentation dams, where the fly ash from the burning of the bagasse is processed.

Large amounts of the organic material are dissolved in the water used in the scrubbing process, which makes this a potentially viable source of feed for anaerobic digestion. The biogas produced could be used in heat recovery or boiler feed gas processes (Kamali et al., 2016).

There are a growing number of high-density animal production areas such as chicken farms, cattle feedlots and pig farms, which service the large metropolitan areas of the country (Republic of South Africa, 2003).

2.4.5 *Current commercial biogas operations*

SABIA maps major biogas-related projects on its website, as a means of tracking the development of biogas in South Africa. A total of sixteen projects are listed, with a total potential output of approximately 25 MW electrical power, and an additional estimated 1 MW produced for boiler feed. These figures are tabulated below.

Table 2-4: Current and imminent major biogas producers in South Africa (Southern African Biogas Industry Association, 2015)

Location	Feedstock	Nominal Power (MW)
Queenstown, Eastern Cape	Landfill waste	6.0
Durban, Kwazulu-Natal	Landfill waste	6.0
Bronkhorstspruit, Mpumalanga	Manure	4.6
Mossel Bay, Western Cape	Refinery wastewater	4.2
Northern Works, Gauteng	Wastewater	1.2
Driefontein, Gauteng	Wastewater	0.8
Darling, Western Cape	Bovine manure	0.6
Grabouw, Western Cape	Fruit pulping waste	0.5

Location	Feedstock	Nominal Power (MW)
Cullinan, Gauteng	Slaughter waste	0.5
Springs, Gauteng	Slaughter waste and organic waste	0.4
Jan Kempdorp, Northern Cape	Slaughter waste	0.1
Durbanville, Western Cape	Pig manure	0.1
Riversdale, Western Cape	Slaughter waste	0.1
Durban, Kwazulu-Natal	Grass	0.02

Table 2-5: Known significant biogas from wastewater producers in South Africa (Southern African Biogas Industry Association, 2015)

Location	Feedstock	Wastewater Treatment (MLD)
Stellenbosch, Western Cape	Wastewater from wine production process	4.5
Stellenbosch, Western Cape	Wastewater from beer production process	1.0

Although the figures remain small when compared to the national energy grid of approximately 35 – 40 GW (Eskom Holdings Limited, 2015), and the REI4P, the information provided indicates the propensity of the market to move toward a specific target; i.e., waste.

Based on the projects listed, it becomes apparent where opportunity currently lies in biogas implementation in South Africa; wastewater from municipal and industrial processes are by far the most significant contributor to the 25 MW potential.

2.4.6 *Prospects for carbon credits and taxation in South Africa*

The potential sale of carbon credits and tax relief provide attractive leverage for South African multinational companies to obtain financing from international markets and investors (Karani & Jewasikiewitz, 2007).

2.5 Enablers of commercial biogas implementation in South Africa

The first sub-problem is the identification and understanding of the factors that would enable commercial biogas implementation in South Africa.

Salient information from the discussion topics of the literature review is re-emphasised and condensed to formulate research proposition 1.

2.5.1 *Energy security*

Biogas as a primary product of AD can be utilised as a thermal fuel or converted into electricity and other increased value products, which improves the diversification of energy supply of any system. To re-emphasise the factors of energy security as described by (World Economic Forum, 2017) is listed as follows:

1. Self-sufficiency and diversity of supply;
2. International security and geopolitical risks;
3. Infrastructure resilience and flexibility;
4. Economic risks and increases in demand;
5. Level and quality of access;
6. Governance and emergency response mechanisms.

It is conceivable that biogas addresses one or more of these factors in the South African context.

2.5.2 *Environmental security*

The life cycle analysis of a biogas process indicated that it could produce beneficial products such as digestate and biogas from organic waste or by-products. The contributing factors of biogas to environmental security and sustainability can be summarised as follows:

1. Greenhouse gas abatement;
2. Odour and pathogen mitigation;

3. Increased water efficiency;
4. Production of organic fertiliser;
5. Improved water and sanitation management.

Environmental security could be realised in the agriculture, municipal and industrial sectors as all these sectors have biogas feedstock potential.

2.5.3 *Availability of feedstock*

The White Paper on renewable energy identified the agriculture industry in South Africa as a reliable and significant potential feedstock for bio-energy processes including biogas.

Today, increased urbanisation and population growth have led to an increased strain on municipalities' wastewater treatment facilities, which could use biogas to alleviate capacity constraints and improve efficiency.

Manufacturing industries release vast amounts of wastewater into the water ecosystem, which has been shown to contribute to worsening water quality and river pollution. Based on the literature, high organic loading in industrial wastewater streams present opportunity for biogas dissemination in industry.

2.5.4 *Research proposition 1*

The potential for improved energy security and environmental security gained from the dissemination of biogas, as well as the availability of feedstock, are the main enablers for commercial biogas implementation in South Africa.

2.6 Inhibitors of commercial biogas implementation in South Africa

The second sub-problem is the identification and understanding of the factors that would inhibit commercial biogas implementation in South Africa.

Salient information from the discussion topics of the literature review is re-emphasised and condensed to formulate research proposition 2.

2.6.1 *Deficiency of biogas-specific legislation, incentives and policies*

The REI4P was fundamental in demonstrating the ability of the South African government to formulate a policy and for the private sector to efficiently execute renewable energy projects that contribute significantly to the national electricity grid.

To date, biogas has not featured in the REI4P projects completed; where renewable energy in South Africa is dominated mainly by wind, solar and hydroelectric power.

It would further appear that the National Environmental Management Act and its various amendments since the Act came into effect in 2008, has not stimulated the biogas industry to grow. It is likely that organic waste, which is a potential feedstock for biogas, is not utilised beneficially, and is rather disposed of in landfills, used as direct fertiliser or disposed of illegally.

2.6.2 *The infancy of the biogas industry*

In the preceding section, it was noted that the uptake of biogas in South Africa has been very limited to date. The limited dissemination is evidenced in the relatively short list of commercial-scale biogas projects presented, and their total contribution to the electricity grid which appears to be negligible compared to the national grid of approximately 40 GW (Eskom Holdings Limited, 2015).

2.6.3 *Research proposition 2*

The deficiency of biogas-specific legislation, incentives and policies that would stimulate or promote the development of the biogas industry, as well as the infancy of the biogas industry, are the main inhibitors for the commercial implementation of biogas in South Africa.

2.7 Conclusion of the literature review

The literature review has considered the possible positioning of biogas in the future of South Africa's energy mix. The contribution of biogas dissemination in South Africa appears to be minor at best, with the renewable energy focus resting on technologies such as wind power, photovoltaic solar power and concentrated solar power. The REI4P contained an insignificant determination towards biogas and bio-energy in general, despite the mention thereof in the government's various iterations of the White Paper on Renewable Energy, the Integrated Resource Plan, and the National Development Plan.

It is apparent that anaerobic digestion methods present a simple method to produce biogas for energy use such as heating or electricity production and can fulfil a waste abatement function as well. The life cycle analysis of biogas process has been shown to be beneficial to the environment overall, and the use of digestate significantly beneficial to agriculture.

Biogas' significant uptake in the more mature markets such as Poland and Germany, who are large agricultural producers, has been met with challenges but also much success as evidenced by their continued dissemination.

Bearing a paradigm of energy security and environmental security, biogas as a renewable form of energy appears to be a promising yet fledgeling technology for consideration in niche markets in South Africa. Recent project developments point to biogas processes being more viable and potentially integrated into municipal wastewater (sewage) treatment entities, which are presently over encumbered due to rapid urbanisation and antiquating infrastructure.

Private sector industries such as agriculture produce significant amounts of animal and plant waste and by-product but are not necessarily efficiently utilised or mitigated. Furthermore, pulp and paper, sugar, and petrochemical industries produce wastewater of high chemical oxygen demand that negatively impact the environment.

Biogas appears to be unfavourably bundled into the mix of renewable energy technologies and is not fully appreciated for its characteristics other than pure energy output.

2.7.1 *Research proposition 1*

The potential for improved energy security and environmental security gained from the dissemination of biogas, as well as the availability of feedstock, are the main enablers for commercial biogas implementation in South Africa.

2.7.2 *Research proposition 2*

The deficiency of biogas-specific legislation, incentives and policies that would stimulate or promote the development of the biogas industry, as well as the infancy of the biogas industry, are the main inhibitors for the commercial implementation of biogas in South Africa.

CHAPTER 3. RESEARCH METHODOLOGY

This chapter involves the research methodology and design that was used in addressing the research propositions posited in the literature review and provides a rationale for selection of the methodology. The selected research design is motivated, and information on the population and sample for research is presented. The research instrument is explained, which incorporates critical requirements such as data recording and processing, and ethical considerations for this study.

Data collection methods and the analytical approaches are outlined regarding the literature review and chosen research methodology. Limitations of the study are identified for the topic, relevant to the area of study. Validity and reliability of the research are evaluated within the context of the academic literature presented and the rationale for how and why the criteria for validity and reliability of this study are met in utilising the chosen method and design.

Tracy (2010) presents eight significant markers of quality in qualitative research, which the author has incorporated into the research methodology of this study.

3.1 Research paradigm

Based on the nature of research problems identified and the research propositions developed during the literature review, a qualitative research methodology was selected. Bryman (2012) describes a qualitative approach to research as one aiming to emphasise evaluation of words rather than an evaluation of data.

The literature review revealed that a substantial body of research exists in the field of biogas and its related topics, but that the key is enabling and inhibiting factors for biogas dissemination or reasons, why it is incorporated, vary significantly from country to country. It is therefore essential to obtain specific, relevant, and objective information from appropriate respondents, which attempts to address the research propositions. To ensure useful and reliable results, the qualitative nature of this research was methodologically rigorous and followed a pre-defined structure regarding research design, by guidelines from the literature.

3.2 Research design

Within the framework of a qualitative research methodology, several options for research design are available to a researcher. Bryman (2006) describes the five main research designs as follows: experimental, cross-sectional, longitudinal, case study, and similar designs; where these research designs apply to both qualitative and quantitative research methodologies. The selection of an appropriate research design assists in directing the research and is critical to the ultimate validity and reliability of the outcomes (Bryman, 2006).

In considering the outcomes of this study, the most relevant research design would be cross-sectional which would be conducted using interviews with identified respondents.

The cross-sectional research design shall primarily be of an exploratory nature, which allows respondents to contribute to enhancing the validity of the study in present day (Denzin & Lincoln, 1994).

3.3 Population and sample

3.3.1 *Population*

The target population was stakeholders from identified relevant sectors including government, technology developers, farmers, industry associations and researchers.

3.3.2 *Sample and sampling method*

Bryman (2012), discusses various methods of sampling in the context of a qualitative research paradigm and that it is imperative to identify respondents that represent all types of stakeholders potentially affecting the validity and reliability of this study. Purposive non-probability sampling was therefore used to identify interview candidates who would be able to address research questions.

Considering time limitations and the purpose of this research, a proposed sample size for this study was ten respondents, and ten respondents were interviewed between January and February 2018. This sample size, coupled with the semi-structured interview design, is likely to be large enough to reduce the chance of informational redundancy, but small enough that it allowed the research to proceed within the confines of time-constraints and research outcomes for this type of report.

Unfortunately, Respondent number 10 representing a regulatory body was unable to provide sufficiently detailed, and appropriate responses and their responses were therefore excluded from the results of this study.

The research validity of the intended sample size of ten respondents is corroborated in the findings by Guest, Bunce, & Johnson (2006), which indicated that after only twelve interviews they had created 88% of the total number of codes represented by the eventual total of 60 interviews. Guest et al. (2006) discuss the generalisability of their result in light of consensus theory and further posit that it may be relevant to questions that deal with experiences, perceptions and beliefs (and not just structured questions which deal with knowledge only).

Table 3-1: Respondent profiles

No.	Description of respondent
1	University Professor, involved in research and lecturing of biogas and bio-energy.
2	Partner at a major international law firm, based in South Africa involved with REIPPPP contracts and renewable energy.
3	Managing director of a company that built and owns a significant biogas plant in South Africa.
4	Technical director of an engineering, procurement and construction management (EPC) company specialising in biogas projects in South Africa (agricultural sector).

No.	Description of respondent
5	Technical director of an engineering, procurement and construction management (EPC) company specialising in biogas projects in South Africa (industrial sector).
6	Technical director of an engineering, procurement and construction management (EPC) company specialising in biogas projects in South Africa, with 20 years' experience in the European biogas industry.
7	Process engineering manager in charge of developing biogas at one of the largest municipal wastewater treatment companies in South Africa.
8	Engineering manager of a multi-national beverage producer, responsible for a wastewater-to-biogas facility at one of their plants in South Africa.
9	Biogas projects director at a non-profit sustainable energy projects facilitation company in South Africa.
10	Regulatory and compliance officer at a regulatory entity in South Africa.

3.4 The research instrument

Interviews with research instruments may be of structured, semi-structured or unstructured format. Structured, semi-structured and unstructured face-to-face interviews were considered as options of observation schedule. Structured interview questions would impose limitations in this scenario because of the variety of fields of specialisation of the stakeholders in the industry. Unstructured (open-ended) interview schedule may provide data that could be difficult to analyse regarding the envisaged thematic analysis; crystallisation and triangulation techniques may be unsuccessful if the data are too diverse.

It was decided, therefore, that the optimal data collection method would be semi-structured face-to-face interviews with respondents; this method benefits from allowing subjectivity in answering questions, but simultaneously keeping the research focused allowing subsequent thematic analysis.

As discussed in the literature review, the field of biogas tends to be broad, and bearing cognisance of the delimitations stated, it was essential to use a focused set of determinants and desired thematic outcomes to address the research propositions appropriately.

The critical challenge which poses a potential risk to the validity of this type of research is that access to interviewing the appropriate stakeholders is required. Since the research encompasses both enabling and inhibiting factors, which spans across various fields of specialisation and industries, the quality of the research depended on adequate representation of an industry. The author proposes that these elements have been covered as evidenced by the respondent profiles.

The interview schedule that was used conforms to the semi-structured research methodology employed in this study. The questions to the respondents provided a guideline, which invariably unravelled additional points of interest and further lines of inquiry. In consideration of the field of expertise of each respondent, particular questions were omitted, and others added during the interview.

3.5 Procedure for data collection

3.5.1 *Data collection instrument*

The data collection method included primary sources of information using an observation schedule with face-to-face interviews. The author selected face-to-face interviews in a quiet and comfortable environment, devoid of distractions, which would allow the accurate recording and capturing of interview data.

3.5.2 *Ethical considerations of data collection*

Due to the ethical requirements of qualitative research, it was a pre-requisite for respondents to give consent before participation in the interview process. A formal letter of invitation including a letter of consent was prepared for this purpose and given to each respondent timeously before interviews. A formal, structured approach such as this, was replicated precisely for every respondent, ensuring ethical expectations were managed and ensured replicability of the process which would imply increased reliability and validity.

3.5.3 *Data management and storage*

The data collected from respondents, being the interviews themselves, were recorded using a professional USB condenser microphone onto an open-source voice recording platform. The high-quality audio was produced and saved as a free lossless audio codec (a studio-quality audio format). The choice of face-to-face interviews in every instance ensured that recordings were clear and uninterrupted. Audio recordings were subsequently transcribed by a third-party and checked for consistency and accuracy.

All data collected were stored in digital format on a password-protected, encrypted, data storage medium. Each respondent was given the option of requesting the digital recording and transcription.

3.6 Data analysis and interpretation

Processing of qualitative research data involves specific steps followed rigorously to ensure rich rigour principles and repeatability of the research. The following outline, adapted from Wotela (2016) was used:

1. Transcribe interview audio to text;
2. Conceptualise the themes identified in the literature review;
3. Fragment the themes from the literature review;
4. Conceptualise the themes identified in the data;
5. Fragment the themes from the data;
6. Perform coding of the data.

Denzin & Lincoln (1994) describes methods of analysis of qualitative research: conventional, directed, summative and thematic. The data were subsequently analysed using thematic content analysis. To adequately interpret the data, thematic analysis generated themes (also known as codes), which resulted in the information required to address the research questions as described in the literature review.

Thematic analysis is relevant for this study because together with the consistency matrix and interview guide as guidelines, a tie-in with the themes developed in the literature review.

3.7 Limitations of the study

Due to the relatively small sample size of respondents, the possibility always exists that emerging themes may not be congruent across respondents and that respondents were subject to opinion bias. The techniques of triangulation and crystallisation (Golafshani, 2003; Johnson, 1997) were considered and incorporated into the coding and thematic analysis to mitigate the effects of opinion bias.

3.8 Research validity

Methodological and disciplinary standards ensure a rigorous, high-quality process that results in a broad application of the research results. In literature, validity deals with the integrity of the research process and its findings and conclusions (Creswell & Miller, 2000). As cited in Tracy (2010), "For qualitative research, credibility is earned through reliability, replicability, consistency, and accuracy (Golafshani, 2003, p. 843)". The strict methodology applied in this research ensures validity.

Tracy (2010) states that "The concept of triangulation emerged within realist paradigms that aimed to rid research of subjective bias", which is supported by Denzin & Lincoln (1994) as cited in Tracy; if two or more different sources of data converge on the same conclusion, then the conclusion is more credible. Findings are discussed in the results chapter, where the convergence of opinions of several respondents across several topics is demonstrated.

3.8.1 *External validity*

External validity also termed transferability and the potential for research to be generalised (Tracy, 2010), has been considered firstly by the accurate definition of delimitations of this study in the context of South Africa. Secondly, it is anticipated that the respondent selection adequately addresses main stakeholders given that South Africa's biogas industry is relatively small compared to the mature biogas markets internationally.

Considering the delimitations and assumptions of this study, the author suggests that, based on the outcomes of the research process, external validity has been adequately satisfied.

3.8.2 *Internal validity*

Internal validity is also known as credibility and trustworthiness, (Hsieh & Shannon, 2005). The author of this research contends that internal validity measures were duly satisfied, by specific mention of the following considerations:

1. This study makes use of published journal articles that are:
    a. Peer-reviewed;
    b. Inclusive of recently published research, mostly within the past three years;
    c. Inclusive of literature from authors who have multiple publications in their respective field and could reasonably be considered specialists;
    d. Sourced from journal publications that span different perspectives and objectives, such as, for example, *Energy*, *Energy Sustainability Reviews*, and *Policy*;
2. This study makes use of information contained in reports that are published by reputable, recognised worldwide programmes and initiatives, corporate institutions and government agencies that have previously had or have the potential to impact policy-makers in government. Sources used include:
    a. World Economic Forum;
    b. World Bank;
    c. International Energy Agency;
    d. United Nations and its associated entities.

3. This study makes use of accords, Acts, policies and specific information from institutional frameworks that are stakeholders in South African government including:
    a. Various Acts of Parliament of the Republic of South Africa;
    b. Department of Energy;
    c. Council for Scientific and Industrial Research (CSIR);
    d. The Presidency and the National Development Programme (NDP).

3.9 Research reliability

This study intends to meet the criteria of reliability in qualitative research as defined by Tracy (2010), where the reliability is dependent on whether the research process is described in a detailed, replicable manner. In addition to the detail already presented that addresses research rigour, the following considerations were incorporated into the research to enhance and ensure its reliability:

1. Ethical considerations were identified and addressed in the research proposal phase, which presented the reader and the participants with detailed procedural information to ensure a structured and rigorous process devoid of ethical problems;
2. Profiles of potential respondents were based on the type of stakeholder input required by purposive non-probability sampling techniques; this selection method allows future similar research to be replicated in South Africa or another country;
3. The purpose of the research and consent request to participants was addressed in the research proposal, and was communicated to respondents;
4. The data collection process was sufficiently structured to make it a replicable process.

CHAPTER 4. PRESENTATION OF THE RESULTS

4.1 Introduction

This chapter presents the results obtained from the qualitative research process which used semi-structured interviews as the research instrument. Thematic analysis was performed on the transcribed interviews, noting that not all respondents answered all questions and that some provided additional views that were not explicitly probed further.

Results are placed into categories of within research proposition 1 or research proposition 2, which are broadly responses relating to enabling and to inhibiting factors respectively. Sub-headings have been included to focus the results for following summary and discussion.

Respondents offered their perspectives within their contextual knowledge of specific sectors: agriculture, municipal and industrial.

4.2 Results pertaining to research proposition 1

Results pertaining to energy security and environmental security were found to be interrelated, and it was decided to present these results together, but separated based on the sector to which they apply. Additional observations that pertain to the enablers of biogas implementation that were not posited in the research proposition are also presented in this section for later consideration in the discussion.

4.2.1 *Energy security and environmental security: agricultural sector*

Respondent 4, being the owner/developer of a large biogas plant in Gauteng, explains that the primary feedstock to their biogas plant is cattle manure from the nearby cattle feedlot and food waste from large industries. Abattoir waste is also received by this facility instead of having to go to a hazardous landfill or specialised wastewater treatment plant. The plant is located on the periphery of the urban area which facilitates feedstock availability. They charge a 10% gate fee which is very low compared to landfill gate fees; this cost structure was done so at the inception of the project to attract investors and ensure that feedstock was secured.

Respondent 7 suggests that biogas is particularly attractive as a waste abatement and energy production means for piggeries, dairies and feedlots, as the manure is centrally collected and can be used on site. Respondent 9 said that pig farmers, in particular, appreciate the deodorisation properties of the biogas process and that farmers save between 40 – 50% of waste costs being landfill gate fees, transport and handling of the pig and farming waste.

Respondent 9 gave the example of an abattoir in Jan Kempdorp with a biogas plant that saves R50,000 monthly on waste disposal (the waste is condemned waste blood and organs). The biogas plant reduces the abattoir energy consumption between 40 – 55% because biogas on that site is used to preheat water and to save on waste preparation for disposal. Respondent 9 explained that a particular off-taker of the solid fraction from this abattoir's biogas plant uses it as inorganic fertiliser for worm farms which then produces even better compost for nurseries.

Regarding agricultural fertiliser practices, Respondent 9 was critical about chemical fertilisers in agriculture and argued that after many years of fertiliser application to soil, farmers have to use lime to get rid of the salts that have built-up in the soil. He further noted that plants cannot absorb the excess highly concentrated fertilisers, and contrasts this with digestate, which is dilute, immediately absorbed and did not lead to over-concentration in the environment.

Respondent 5 also noted that many agricultural industries import inorganic fertiliser, whereas the digestate from these wastewater treatment plants can benefit agricultural sectors quite directly and cheaply.

Respondent 6 further compared the use of inorganic fertilisers to digestate and pointed out that fertiliser does not put carbon back into the soil, whereas digestate does; carbon retains nutrients for longer and prevents runoff of nutrients. Carbon also provides an additional surface area for nutrients. On an overall basis, digestate decreases the salinity of a liquid also nitrogen has ammonia becomes volatile and is manageable.

4.2.2 *Energy security and environmental security: municipal sector*

Respondent 1 offered extensive input regarding municipal WWTP. He believes that there is more potential for biogas in wastewater treatment in South Africa compared to the agriculture sector and suggests that the urban setting of wastewater must be considered as opposed to rural wastewater treatment facilities which are generally much smaller and remote.

Considering biogas in municipal WWTP, for example, Respondent 1 cited the Enstra WWTP in Springs that was built in the 1930's, where the infrastructure for biogas production exists but due to lack of maintenance, it no longer functions. He further noted that in most wastewater treatment plants, biogas is generated but not captured nor utilised beneficially such as for heating and electricity generation; and further suggested that potential for biogas in urban wastewater treatment areas is significant because WWTP capacities in Gauteng are typically 150 million litres per day per facility. Respondent 4 offered a similar perspective that there is a potential for these wastewater treatment plants to offset their energy use. Respondent 1 stated that the energy from biogas could be just enough to run a WWTP and if adequately operated, be an efficiency enhancer for the facility. Rather than trying produce electricity for the grid, says Respondent 1, biogas could potentially power at least 50% of a wastewater treatment plant which is significant if one considers the large electricity users in this type of plant.

Respondent 1 argued that, before embarking on ambitious infrastructure projects in biogas, the "low hanging fruit" needs to be explored first; for example, using biogas as a thermal fuel to heat a digester itself, which improves the efficiency and output of the WWTP. Particularly in the Highveld, he added, the ambient temperatures are relatively cold in the winter, with the reaction rate at 30°C is much higher than at 20°C. The point is that at lower temperatures, the AD processes are slower and less efficient.

Respondent 3 referred to a design handbook for WWTP from the 1940's that includes AD a standard part of the design, where the design intent was not to maximise biogas output but to treat nitrogen in the solid waste. According to the old designs, says the respondent, biogas produced should be used to heat the digester to 30°C which improves the efficiency. Considering the standard design philosophy of WWTP, if one had to audit the current digesters, it would emerge that many digesters do not function at all or just have been taken out, which contributes to the WWTP's being declared overcapacity.

According to Respondent 3, large WWTP's could self-supply at least 60% of their electricity needs; and for a small municipality, this would represent a significant saving on expenditure. The most commonly-used digester in South Africa is the "cold" type in WWTP. Of all the wastewater treatment plants managed by the utility, more than 90% have AD's, with some producing biogas. Not all these facilities, however, have the right infrastructure to produce and capture sufficient biogas since there are additional mixing and heating necessary to improve the efficiency of these units. Respondent 3 added that old digesters use cold digestion which means very long residence times for the sludge (slowing down the process and meaning a lower overall capacity) and most of the gas produced is released into the atmosphere without flaring. Concerning scale and financial considerations, biogas captured could generate electricity and waste heat could be used to heat the process, leading to an increase in efficiency.

Respondent 5 suggests to consider only implementing significant beneficiation of biogas on WWTP that receive more than 5 MLD of effluent; the most critical cost considerations are additional infrastructure such as gas cleaning. He added that biogas production could provide further benefit from an operational point of view in that it could serve as a backup measure for critical systems in the event of utility power failures. Since municipal entities rely heavily on electricity to operate their wastewater treatment plants, Respondent 5 felt strongly that a net positive business impact may be realised if biogas is deployed at the WWTP's and estimates generating more than 60% of the needs of the plant, with an approximate 10-year payback period.

Respondent 7 provided an example of a plant in Cape Town that produces and upgrades biogas for sale in the local area, which is produced from municipal wastewater. He affirms that there may be more potential in gas upgrading than electricity generation. Respondent 7 further added that biogas seems to be more viable as a transport fuel; and that this has been demonstrated in the United States. Such an industry would be potentially viable in South Africa.

Figure 4.1: Animal manure and food waste stockpiling at a South African biogas plant (researcher's photograph)

4.2.3 *Energy security and environmental security: industrial sector*

Respondent 5 supports the benefits of industrial wastewater contributing to the existing municipal wastewater treatment instead of landfills or other alternatives. Their WWTP management is currently pursuing the strategy to encourage industrial wastewater producers to use the municipal infrastructure. The respondent noted that standard disposal of wastewater causes significant odour and pathogens and present hazards that contradict waste management regulations and guidelines. Respondent 5 explained that they aim to have biogas digestate tested extensively to prove to agriculture that it serves as a benefit and mitigates the risks of standard disposal, however, that it seems to be challenging.

Respondent 8, a beer-brewer, reports that their industrial wastewater treatment facility produces biogas that is directly used in a gas steam boiler, also being economically beneficial by providing 10% of the entire site energy, which he states as significant. Respondent 8 further noted that because they reduce their chemical oxygen demand (COD) using the biogas process, that the load on the municipal cost for discharging that effluent is decreased materially. The plant has been in place for a long time, and they are currently investigating bringing the water produced by the digester to potable grade quality which would further benefit their water-balance and sustainability.

Respondent 8 believes that the value proposition of AD should be packaged as a means of waste remediation rather than power generation. Their business is an example, where the initial system priority was to reduce the COD and BOD strength of the effluent water they discharge. Respondent 8 added that the practice of using AD is done by many breweries, which are known to have high chemical oxygen demand in their wastewater output. For industrial applications, the total cost of ownership is relatively low.

Respondent 9 contends that biogas from any process has many uses such as heating, conversion to fuel, compressed natural gas, or in an engine, and could be particularly useful to industrial entities. He adds that pyrolysis is another recent use where digestate is used as the energy fuel, and the energy is used to convert waste plastic into useful fuel oil. The overall impact of this project, for example, is significant from an energy perspective, while landfill space requirements are significantly reduced.

Respondent 8 explained that there is a small overall electricity user base to run a biogas process, but that is much less than the overall energy generated.

4.2.4 *Environmental security: waste abatement and carbon abatement*

According to Respondent 1, the methane in biogas (being about 45% of the total gas composition) is approximately 27 times more potent as a greenhouse gas than carbon dioxide, and that it is, therefore, vital to managing biogas production correctly. Respondent 5 also affirmed that methane has 23 times the greenhouse gas effect that carbon dioxide has.

Respondent 1 states that in WWTP, for instance, if the methane which is usually produced is allowed to escape to the atmosphere instead of being captured and burned, it would have a higher impact on the environment. The respondent concluded that a biogas process must be operated efficiently and adequately for it to provide a benefit to the environment. Otherwise, it would have no benefit. Respondent 3 also emphasised that biogas need to be correctly fitted into a waste cycle for there to be a zero-net effect on the environment. He also added that biogas as an energy source displaces the necessity of using other potential sources of energy such as fossil fuels.

Respondent 1 highlighted that WWTP consolidates water from various sources including industrial wastewater; this adds a significant amount of usable water and substrate into the process which would otherwise have ended up in rivers or the water table, and that improved water recovery means improved water security.

Respondent 4 performed a quick environmental life-cycle analysis on his biogas facility, demonstrating the effect of the biogas plant on the immediate environment:

- Before the implementation of the biogas plant, animal manure was previously stockpiled at the cattle feedlot, and during periods of rain the manure would run off into the nearby catchment areas and river. This represents environmental contamination to an extent because of the scale of the farming – high-intensity farming produces extensive urine and manure which in high concentrations contaminates groundwater. The effects of odours of the stockpiled manure were previously reported to be a nuisance for a nearby wedding-venue;

- Now, the biogas plant uses an 18-day rotation cycle to minimise the potential for groundwater contamination;
- The plant receives high-odour hazardous waste from a facility in Midrand, which previously paid high fees for disposal. The waste becomes inert, and the odour is removed.

Respondent 5 sees biogas as a renewable form of energy that not only mitigates the increasing cost of electricity but also provides an environmental benefit by offsetting GHG emissions of methane that would have been emitted.

Respondent 6 emphases that it is difficult to quantify the cost of biogas as an energy source when one has to consider all the beneficial environmental factors, for example, how much greenhouse gas would have been emitted into nature. Respondent 6 noted that there are clean development mechanisms which can calculate the greenhouse gas factors for the technology and provides a global warming mitigation factor but added that the benefit is significant without needed to do any calculation and that it depends on the authorities of interest.

Respondent 7 provided a similar view to Respondent 6 and stated that the benefits of biogas are less easily measurable than conventional processes and that the benefits depend on the size, the feedstock used and the location. Respondent 7 suggested that digestate can be viewed as a waste product if it is not beneficially used or adequately managed, and further mentioned the efficacy of biological processes to treat digestate up to potable water standard by adding further systems such as aerobic processes.

4.2.5 *Environmental security: pathogen and odour mitigation*

Respondent 1 generally supported the ability for the AD to mitigate pathogens from a feedstock but qualified digestion itself is not necessarily specific for pathogens. He added that, in general, if one had to consider WWTP, the untreated sludge is sent to landfill paddies and subjected to a chlorination step that removes pathogens, which in itself is not always 100% effective.

Respondent 3 argued that biogas processes do not necessarily treat pathogens and that although some may not survive the anaerobic conditions, there are those who do survive. For the sterilisation of potential pathogens, an additional process such as pasteurisation would need to be adopted. The respondent added that strict regulatory requirements could stipulate a pasteurisation step which includes heating material to 75°C – either at the intake or outlet and that this energy input cost to pasteurise the product is a trade-off that needs to be considered.

4.2.6 *Technological readiness*

Regarding technological readiness, Respondent 1 argued that WWTP use the AD as a standard infrastructure, and provided that there is capital investment available, facilities can quite easily be fitted with equipment to recover and derive benefit from the gas. Respondent 1 added that biogas technology has been around since the 1930's and is not a limiting factor for its dissemination. According to Respondent 1, the factors to consider, however, are the maintenance of the WWTP and whether municipalities are correctly geared with the skills to handle a potential biogas capture upgrade. He added that in high-density population areas, many of the older WWTP are not being very well maintained.

Respondent 3 contends that although there are a variety of AD designs, no matter which one is used, biogas will be produced if the microbiology in the digester is correct and the unit is appropriately operated. He added that even the crudest type of design can still produce biogas if it is operated correctly.

Respondent 3 felt that AD's are not appropriately operated at South African WWTP's, which is the cause of the inefficiency and that the existing infrastructure should be first be used to improve the overall efficiency of treatment, and secondly to derive biogas.

Respondent 4 spoke about South Africa's capability to supply and install all necessary components locally except for the CHP units. At their plant, Respondent 4 uses co-digestion where two separate wastes are received by the facility; a solid and a liquid stream and added that the plant's robustness had been tested to handle different feedstocks over the last two years. He stressed the importance of learning which key parameters are needed to monitor the health of the plant (such as acidity, where fruit is then added to manage); if the health of the plant is not monitored or managed correctly, the microbes die, and the process does not produce biogas.

Respondent 7 provided the perspective that project costing in South Africa is often linked directly to the location from which the equipment is supplied. There are technical issues where standardised equipment is used, and safety requirements are not met. For example, to cut costs in the design and construction phase, Danish and South African technology are combined, but the outcome is not always practical. The primary barrier is not technological availability, but rather a lack of skills regarding the operation of biogas plants.

4.2.7 *Feedstock security*

Respondent 3 suggests three main factors for the success of a biogas project:

1. Availability and proximity to feedstock;
2. A consumer of electrical energy or thermal energy;
3. A secured off-taker of digestate.

According to Respondent 6, feedstock management is one of the most critical factors for a successful biogas project, and all South African developers have struggled with this concept. Securing feedstock and offtakers of digestate is critical to the success of the project, which means characterising the input stream and undertaking due diligence. Often designers or developers of a process will look at the maximum output and not necessarily average output of the farmers and therefore the due diligence is not done correctly.

Respondent 9 lived for 30 years in Germany and had been practising biogas since 2006, and in 2009 developed a biogas system and brought the technology into South Africa. His company represents the largest regarding anaerobic digestion in Sub-Saharan Africa, and they currently have seven operating facilities. Their company has done cursory research that showed a potential of more than 4 GW worth of electricity production available from environmental sources in South Africa. Additionally, he added, the process can help mitigate water management problems because the process is an environmentally friendly water source.

4.3 Results pertaining to research proposition 2

Results pertaining to legislation, incentives and policies, as well as the infancy or state of the industry are presented in this section. Additional observations that pertain to the inhibitors of biogas implementation that were not posited in the research proposition are also presented in this section for later consideration in the discussion.

4.3.1 *Deficiency of biogas-specific legislation, incentives and policies*

Respondent 1 believes that when analysing costs of electricity from a renewable source/alternative source, it is also possible that previous economic analyses did not anticipate the significant electricity price increases promulgated by Eskom over the past decade. Since most WWTP in South Africa is to some extent parastatals, incentivisation and subsidy-type arrangements are probably questionable. Once the enforcement of the policies of the Department of Water and Sanitation is a priority, the uptake of biogas may probably increase. Respondent 1 further noted the importance of capital structuring for possible retrofitting of WWTP with biogas capture units; this will rest mainly on whether there is enough political will combine with an appropriate policy to motivate that it is, in fact, viable to the various budget makers.

Respondent 2 provided perspectives as a legal professional experienced in the renewable energy sector in South Africa. According to Respondent 2, biogas probably needs to be put into its category as it seems to have lost out in South Africa as renewable energy. In general, renewable energy technologies have been lagging for the past two years due to the failure of Eskom to sign the bid window agreements of the REI4P that are still outstanding. Respondent 2 surmised that had it not been for the delays we would probably have been further ahead than we are now; the political dispensation needs to pay attention to renewables from a resource and economic point of view. Availability of finance has always been consistent in respect of the REI4P and has never been an issue until the 2015 – 2018 uncertainty regarding Eskom and the government's position on renewables.

Respondent 6 discussed the viability of biogas in municipal WWTP and explained that it had been successfully demonstrated in municipalities around the world. In South Africa, however, the Municipal Finance and Management Act (MFMA) has the restriction of a three-year agreement limitation. In the example given by the respondent, a biogas plant needs to be run by the developer's team otherwise the banks would not finance it if the municipality ran it, but that the developer was prevented by the MFMA to enter into a long-term agreement. The overarching steps of the wastewater treatment project partnered with a municipality requires strict oversight on municipal actions and a clear view upstream to hold them accountable for the feedstock process. The strategic approach a developer takes on capital expenditure may be attractive for municipalities that are cash-strapped.

Respondent 2 mentioned that there is a political risk aspect for which many international investors do not have the appetite. He cited that political risk, therefore, constitutes a barrier and further added that his interaction with various stakeholders was promising regarding the REI4P process; that it was well-defined, transparent, and that operational costs and infrastructure costs have decreased since the previous REI4P submission in 2015. Wind power and solar PV, for example, holds well for off-grid scenarios to generate electricity for a particular community or town, and this seems to be the way to position a project and is potentially a mechanism to promote biogas in South Africa.

According to Respondent 2, the advent of public-private biogas partnerships is only in its infancy in South Africa; power producer agreements allow approximately 77 c/kWh in the REI4P, but biogas could not be pursued at this rate. The tariff rate that has been given does not cater for the additional value-added products that biogas can offer as compared to other technologies like wind and solar. If an equivalent rate or metric such as a non-dimensional number could quantify the additional benefits of bio-energies, then one could compare different technologies.

Respondent 3 holds the view that even if the private sector would like to invest in biogas infrastructure for WWTP, the municipalities are bound by the Municipal Finance and Management Act (MFMA). The MFMA stipulates that no agreement lasting longer than three years may be signed with an outside party; this makes private sector involvement and development nearly impossible.

Respondent 3 added that waste management policies and regulations are simple on energy-related aspects of projects, but in respect of waste there needs to be support for responsible management of waste such as the reduction of landfill space. The business cases for biogas projects are sometimes marginal but if policy drives the large industry to react in a more responsible way- such as keeping or reducing their waste of landfills- then only can it be more helpful to support that industry than energy off-takers.

Respondent 3 feels that South African regulatory bodies do not know where to place biogas in policy and regulation. He noted that composters often illegally incorporate condemned waste such as animal organs and blood into their compost, which creates subsequent water contamination and air pollution, and with the waste potentially ending up on a vegetable field for instance. There are many challenges encountered for a biogas plant to obtain licensing to process abattoir waste, as compared to composters who do not encounter the same challenges.

Respondent 3 mentioned that biogas industry stakeholders have been lobbying the Department of Environmental Affairs to either classify biogas under its own rules or to incorporate it with composting to make it easier for biogas developers to apply for a licence. The waste processing licensing process is currently complicating dissemination of biogas unnecessarily, and therefore biogas developers find themselves trying to avoid specific triggers such as a specific capacity, location, or type of feedstock. Due to these cumbersome challenges in regulations, the cost of developing the project increases due to uncertainty and therefore the risk for developers and financiers, impacting the development cost.

Respondent 3 views the development of virtual gas networks in South Africa as an opportunity for biogas. The fact that natural gas, a similar product already has an established market, creates a parity model for pricing of biogas. Having a pricing model makes it easier to assign a value to biogas as a commodity substance, particularly when developers consider sellers and buyers.

Respondent 4 contends that the main reason for the lack of participation of biogas technologies in the REI4P is that the bulk of biogas projects are small. The requirements for participation in the REI4P was costly in that auditors and attorneys needed to be appointed and that there was no guarantee of getting the project. The primary bid put forward was less than 100 c/kWh, which is not feasible for biogas. The subsequent REI4P round 4.5 showed significantly higher tariffs, but at this stage, there is no clear decision on the way forward with the REI4R programme.

According to Respondent 5, there is limited policy and regulation for the biogas industry, and that it is not straightforward for biogas producers on where to apply for a gas generation licence. For municipal entities, funding can be a challenge, and it is encouraged for the private sector to participate in private-public partnerships. Respondent 5 suggests for the wastewater treatment utilities to charge a rate per ton similar to a gate fee similar to landfill sites. Respondent 5 estimates that their business unit processes on average a dry flow of 700 MLD in the eastern Gauteng region. Respondent 5 clarified that industrial effluent is part of the sewer line mix, and the split between industrial and municipal in this particular municipal area is approximately 60% industrial to 40% municipal. He noted that there are highly industrialised areas feeding into this municipal catchment area where the challenges that exist are the standards for industries to discharge into their system. Penalties are charged by the municipalities if the limits are not adhered to by the industries. However, there is a need for development, and if the bylaws or regulations are too strict, the businesses would be discouraged or seek alternative service providers for their wastewater. Respondent 5 added that some industries merely pay the penalties; the businesses look at the cost difference between new on-site treatment facilities as compared to paying penalties.

Respondent 6 asserted that biogas is about compliance and penalties on waste management. In South Africa, the regulatory structure does not cater for biogas to be integrated into a waste management strategy. Biogas will find it difficult to compete in areas such as the REI4P due to low pricing from other renewables, specifically solar PV, and it can only compete if punitive measures are levied against non-compliance. Respondent 6 further adds that, as an alternative line of reasoning, biogas is a dispatchable alternative and requires an appropriate costing and motivation structure. The UK has demonstrated a separate biogas policy as an enabling framework and has classes of waste sterilisation of waste and stabilisation of waste as primary factors. In essence, the Department of Water Affairs in South Africa currently oversees fertiliser and water management, sludge, manure, and effluents. However, there is no separate biogas function. Respondent 6 suggests that biogas policy going forward should not be prescriptive but instead, protective of the industry. The incentives for biogas dissemination are not adequate.

Respondent 7 explained that the birth of the biogas industry in countries such as Denmark and Germany were due to regulations disallowing farmers to spread manure on crops and they, therefore, pulled together to build a central plant and then used the digestate as a fertiliser. Within the overall energy mix, solar PV and wind power are cheaper, and the business case is that investors do not perceive there should be a subsidy for the price difference between the cheaper renewables, and biogas which costs 200c/kWh.

Insofar as the development of a separate policy or incentive, Respondent 7 feels it is unlikely that government via National Treasury would provide a subsidy for biogas. Impetus should not rest solely on grid feed because there are potentially other value-added products on a site other than electricity. Though we do not have a gas grid of sufficient maturity in South Africa, it is something that can be established in the future.

Respondent 7 emphasised that there are some issues relating to the Fertiliser Act; producers do not know how to classify digestate. For someone to register digestate as a fertiliser, it must first be consistent in composition to be saleable. An alternative would be to provide digestate to a composter for use to blend into their product to produce a higher quality product. Respondent 7 further explained that the Act has two classes of fertiliser characterised by their nutrient content, and the third class requires a full composition of the fertiliser which is costly to obtain on a regular basis. Digestate possesses additional components that inorganic fertiliser does not, but this is also dependent on the feedstock.

Respondent 8 provided his view of the industrial wastewater emissions regulations as being in place, but the enforcement is not necessarily done, which poses a threat to biogas dissemination.

Respondent 9 feels that the biogas policy landscape in South Africa is now the same as it was overseas (specifically Germany) in the 1990's and that the primary barrier to biogas implementation is waste producers not following legal acts. The first EIA licence for biogas in South Africa was issued in 2010, and according to that plan, not one control measure has yet been enforced.

Respondent 7 believes that further WWTP biogas dissemination can be successful if the support infrastructure such as separation at the source is appropriately done; this is needed to ensure a non-contaminated organic feed. Biogas presents an alternative to landfill gate fees, and this incorporates the concept of the waste economy. Respondent 7 added that the biogas sector should probably be classified under the waste economy regarding it being able to divert waste from landfill benefits. Municipalities, unfortunately, may view gate fees as a revenue stream where the saving on land for landfill space is not necessarily reflected in monetary terms. Landfills can then therefore still compete with the biogas producers as a cheaper and simpler alternative for waste disposal. The caveat to this is that the enforcement of regulation depends on the local municipalities and is often not done correctly.

4.3.2 *The infancy of the biogas industry*

According to Respondent 1, biogas tends to be underutilised considering the size and potential of South Africa's industry, the growth in its major cities, and the wastewater treatment plants that are associated with them. He added that there is a definite requirement for the AD because the deactivation of the solids fraction from municipal wastewater treatment plants needs to be done efficiently and, in many cases, it is not.

Respondent 2, speaking from a senior legal perspective, indicated that little is known about biogas in the non-technical sector, and the lack of uptake could be attributed to an education issue; the limited success of biogas thus far in South Africa could be attributed to lagging supportive regulation. Respondent 2 argued that the lagging educational aspects feed into the lagging regulatory aspect, and the aim should be for private and government initiatives to have unity in this regard. The renewable energy momentum created by the REI4P may be contagious to biogas and could be spurred on by the worsening Eskom financial situation; it could create the impetus for growth in the renewable sector as compared to the coal-sector, which has been declining internationally.

Respondent 2 explained that prominent insurance companies are no longer underwriting risks on fossil fuels such as coal and that this would ultimately support renewable energy. The availability to place insurance for fossil-fuels will continue to exist, and it is a requirement for bankability of a project. However, the respondent noted that it has started to become expensive to ensure coal-risks. The increasing pressure placed on coal and fossil-fuels insurance projects relate back to the UN prescription on atmospheric emissions. A declining coal market globally is perhaps positive for renewables since the cost of coal power therefore increases. The delays experienced by the Eskom coal power stations, Kusile and Medupi, compared to the absence of delays in renewable energy projects, create the perception experienced by the coal industry. Unquestionably there is a foreign direct investment into South African renewables, and it must be so because the government does not have the funds.

Respondent 3 perceives the biogas industry development as being slow over the last decade, but over the last three years (2015-2017), increased commercial interest has been established. The raised awareness of biogas in South Africa became apparent in 2015 at around the time that the Bronkhorstspruit biogas plant was commissioned, having a capacity of 4.6 MW. He added that the number of biogas plants in development or under consideration increased relatively substantially since then.

Respondent 3 notes that people's perception of biogas plants needs to change in that much more patience in running the process is required. It takes only one biogas project failure that results in a reluctance to grant finance to new biogas projects. A recent situation where a digester did not work correctly resulted in the whole industry becoming aware and critical of it, but after six months new management running the plant and it was producing as designed - this information did not receive the same publicity or attention. The onus then rests on the designers to re-convince the developers that the biogas plants do work. On the whole, Respondent 3 is convinced that financing is not a barrier for biogas dissemination, but it is instead the financier's approach to evaluating biogas projects insofar as risk is concerned.

Respondent 4 perceives the biogas industry to be in its infancy and that the smaller scale opportunities may be higher than those at the more significant utility scale. Large-scale (defined as above 1MW) projects are not straightforward to implement and require an electricity generation licence. Although the projects are viable, margins are low and the payback period is more extended than what is typically expected from entrepreneurs and venture capitalists. Their project took two years to produce positive return; this was made possible partly by having supportive shareholders such as the Industrial Development Corporation. Private equity firms with the long-term sustainable mindset are needed; the loan payback horizon for this project, in particular, is between seven and eight years and then shareholders will start to see income. Nonetheless, biogas projects have access to cheap funding from institutions such as the Industrial Development Corporation (IDC), and the Development Bank of Southern Africa (DBSA). Respondent 4 notes that South African commercial banks would not take the risk of biogas at this stage and believes that this will change in future when more projects become commercial.

Respondent 6 perceives the biogas industry as a young industry in need of skills; the market is marginal as it is, and for skills from overseas historically comes with a development price tag. Respondent 6 stressed the importance that biogas applications are broad and each business model is different, where each case must be considered individually.

Respondent 7 believes that exposure to biogas is at present less compared to other renewable forms of energy, but there is a high impact shown for biogas businesses that already employ it. Respondent 7 perceives biogas to be an infant industry, with some innovators and risk takers, of which more are needed. The industry appears to be a small market for now, and work needs to be done to assist its growth. Gaps that currently make biogas non-viable are not technological but relate to skills such as feedstock management and product management. To better support biogas, one needs to consider all the products of biogas. Where there is a negative sentiment on biogas, this is mainly due to the consequences of weak agreements, lack of skills and inadequate feedstock management. The agricultural sector is a small market and failure of one product or project easily causes changes in perception in the whole industry.

Respondent 8 stated that there had been an increase in the number of opportunities and efficiency of biogas processes and these continually need to be revisited to see what is available the public perception always enquires about green projects.

Respondent 9 offered a farmer's perspective in that farmers in South Africa often do not realise the investment that they have already made in managing their agricultural waste products. Typically, farmers use irrigation to water down their waste which reduces the overall organic content. Respondent 9 added that the market for digestate in South Africa is not straightforward because farmers in South Africa are not sophisticated in their fertilisation regimes: applying inorganic fertiliser to their crops three times a year only.

Respondent 9 explained investors' current view of the finance in renewable energy is an expectation of revenue after one year of operation. However, in biogas investors should expect revenue only after three to five years of operation. Biogas project success remains pivotal on feedstock management. When positioning biogas as an electricity producer, people do not see the additional benefits when they switch on an electric user; it just comes off the grid.

Respondent 9 was critical of the food-producer industry in that it may not fully appreciate what it is paying for waste-disposal costs on a monthly basis. The costs are often only realised once project developers have spent time doing the numbers. According to Respondent 9, the perception of biogas is stuck on peripheral issues such as tariffs- these are not issues. The Development Bank of South Africa currently has over R300 million for biomass and biogas projects available, but a decent project needs to be developed; the IDC wants to see a project that closes the cycle from the waste source to product and back to the waste sources.

Respondent 9 elaborated on the effect of enforcement and control of the already existing legislation in the waste disposal and agriculture sector and mentioned that there are farmers that feed chicken manure to cattle which is of course illegal.

Respondent 3 was critical of developers and owners assigning blame to the equipment and the design, but they do not have the patience for operating the plant and understanding the controls. Respondent 3 suggested that a knowledge database needs to be developed on how to operate these plants and can be shared among the different users. To produce a standard or a good practice document that is centrally accessible to all this could fall under the scope of the Department of Environmental Affairs (DEA). The DEA already outlines general good practice for water management, stormwater, and wastewater – biogas could just be added to it.

Respondent 6 indicated that there is a high level of interest in the subject in academic research fields such as gas yield, life cycle costing, and digestate, and almost every university in South Africa has its biogas/bio-energy champion. Unfortunately, however, this research is seldom integrated into the industry because holistic commercial aspects are not considered adequately in the technical research. Many of the technology suppliers for the plants built in South Africa come from Europe and have a university or academic background, continuously researching this big field and have built a pyramid of competent and educated people. Respondent 6 explained that technology is publicly available for biogas and that it is simple. In South Africa, over the past decade, biogas technology has been promoted by salespeople and not engineers, and that one of the leading issues is opinion engineering. The respondent has seen many biogas plants put together in a haphazard manner, where people are desperately trying anything to get business.

4.3.3 *Competition from alternatives*

Respondent 3 suggested that a barrier for uptake of biogas projects is the relatively low electricity tariffs in South Africa, but that this is subject to increase in the medium-to-long term. Respondent 5 supported the stance that although in the past electricity was cheaper, electricity tariff increases from the utility will continue. Respondent 4 also noted that the cost of grid electricity having increased substantially but that it is still low when compared to international benchmarks. He suggested that if biogas were to be considered in the electricity generation mix as a viable source, off-takers would need to consider a long-term view on pricing and evaluate the non-quantifiable factors such as waste abatement and environmental benefits.

For now, Respondent 3 suggests that biogas is strongly considered as a thermal fuel instead of a potential electrical source and that the concurrent decrease in levelised cost of electricity from solar PV and wind power sources makes biogas less viable purely in the electricity production space.

Respondent 3 believes, however, that biogas as a thermal fuel can be viable and competitive in the South African market, citing a case in point of Denmark being highly successful with biogas injection into the natural gas grid.

Respondent 3 further posits that biogas need not be considered in REI4P or any similar utility-scale incentivisation programme because it is not a wide area distributed solution. When biogas is compared to the more prominent renewable technology options within the REI4P, biogas is much more suited as an on-site, decentralised solution, as opposed to a wide area distributed solution. Respondent 3 gave examples of Germany and the UK, which have hundreds of small electricity producer injection points, but further adds that those grids have been developed to accept multiple injection points, unlike in South Africa. An electricity capacity shortfall of 1,000 MW in South Africa cannot reasonably be addressed by smaller type of producers, of which biogas is one - and therefore cannot compete with the REI4P electricity producers.

4.3.4 *Feedstock security and saleability of digestate*

Respondent 1 touched on the concept of upgrading of digestate to produce higher value products (valorisation) and explained that the United States Department of Energy is currently targeting the production of value-added chemicals from digestate such as succinic, malic and propanoic lactic acids. He further noted that, in theory, the potential economic value of digestate becomes the focal point rather than the potential agricultural benefits such as fertiliser use. The caveat, however, is that the valorisation of digestate is still a decade away and may not yet be applicable in South Africa.

Respondent 3 explained that digestate is not necessarily saleable because the substance is, on paper, weaker than chemical fertilisers and less consistent. He added that crop farming has become much more scientific in the modern age, and farmers would like to know the precise constituents of a potential fertiliser. Fertiliser companies, for example, can be approached by farmers and given precisely the specification that they require. In comparison, digestate is a substance that has a variance against a target, and farmers are not willing to sacrifice on this level of uncertainty. Respondent 3 posited that a market price for digestate is challenging to determine if it is not a consistent product. Where the biological benefits are hard to quantify on paper, more data is needed to convince farmers thereof. AD converts organic waste into a more consistent medium and has the potential to reduce pathogens and odours. Regulations in the European Union and the United Kingdom regarding the use of digestate on soil compels farmers to take the digestate to composters.

Respondent 3 was critical of the fact that although digestate has been reported in the literature to have benefits regarding its nutrient content, it should not be relied upon as a secondary income stream in the business model of a biogas plant. He added that contrary to literature, farmers are reluctant to buy it, and gave the example of Denmark, where digestate is considered waste in the business model assumptions.

Respondent 4 explained that the solid component of digestate is easy to sell to golf courses for example, because it does not have an odour and they mix it in with compost. The liquid fraction, however, remains an issue for saleability although it is 95% water and contains nutrients. According to Respondent 4, what is not appreciated, however, is that there are other substrates contained in the liquid fraction that enhances the quality of the soil such as microorganisms. The respondent’s biogas plant has received positive feedback from their liquid digestate offtakers, but he feels that uptake will increase if the benefits are more precisely quantified to farmers and the market.

Interestingly, Respondent 4 noted that when their biogas project took off, farmers were paid their diesel costs to remove the liquid fractions of digestate from the site but recently the situation has changed, where farmers are taking it for free.

Respondent 6 noted that for medium to large biogas plants, there is cannibalism of projects in the consulting and development space, meaning that projects potentially interfere with each other's waste streams. He added that developers need to be more conservative regarding the estimates of abundant waste streams and concludes that feedstock security is not as abundant as it may appear.

Respondent 6 suggests that because awareness of biogas and digestate is not well-known, farmers are wary of using it as compared to chicken manure for example. He added that another factor is the variability of digestate, and that digestate is not composted and it is not sewage sludge. Respondent 6 said that in the European Union, for example, new projects consider digestate as a cost-bearing item for the first two years and only expects a profit for digestate from year three onwards. Depending on the project, drying and packaging of solid digestate is well-received in the market but represents an additional cost trade-off. The process can manage potential pathogenic organisms by managing pH, retention or residence time and temperature. Respondent 6 suggested that, where the waste is variable, a “big pot” approach can be undertaken – this “blends in” potentially tricky feedstocks with one another.

Respondent 7 contends that feedstock availability is not a problem in general, but that feedstock security is a concern. He noted that few farmers would be willing or able to sign a ten-year agreement to supply, for example, 5 tons per day if there would be penalties involved. He added that due diligence is not always done on the figures supplied by the waste producers; for example, if the farmer stipulates 50 tons per day of manure, is this accurate and sustainable?

Figure 4.2: Liquid digestate in a tank at a South African biogas producer (researcher's photograph)

4.3.5 *Project scale*

According to Respondent 3, in agricultural applications electrical energy can be produced and used on site only (for private business use). However, the scale of the agricultural activities needs to be sufficient to make sense from a business perspective. Respondent 3 gave the example of a farmer that utilises vertical integration with his crops such as the agro-industrial farmer, who would not have to dispose of digestate and could use it themselves. A vegetable post-processing facility on the same site as a farmer producing his primary crops would present a business case.

Concerning project scale for electricity production, a plant producing less than 200 kW is challenging to have a feasible business case. Respondent 3 noted that 200 kW translates into 12 tons per day animal manure feed; which is the equivalent of a 200,000-broiler chicken farm, a 120,000-layered chicken farm, a diary of 1,800 head, or a cattle feedlot of 2,500. There are sometimes also other reasons that facilitate biogas projects such as tax benefits, capital offsets or waste diversion, and these factors require careful case-by-case evaluation.

Respondent 4 corroborated the scale argument of Respondent 3 in that there is a scale at which CHP becomes more attractive and practical; smaller scale is better suited to thermal use. Projects need to be evaluated on a case-by-case basis. The availability of feedstock is contingent on the location: the plant needs to be in proximity to feedstocks for substantial scale projects. Respondent 4 believes that, at present, there are a limited number of feedstock suppliers in South Africa able to meet those requirements.

4.4 Summary of the results

Results obtained from the semi-structured interview process generally displayed convergence of perspectives from respondents, and it was possible to categorise responses accordingly. Respondent perspectives did not appear to display significant opinion bias, because of similar views offered by firstly different respondents and secondly respondents operating in separate fields of expertise.

The outlook on biogas provided is undoubtedly confident and supported by detailed and converging examples of energy security benefits and potential in the South African context, with specific references in the various potential sectors.

The municipal wastewater treatment industry, in particular, seems to have the most latent potential and direct benefit without a need for extensive modifications or capital investment.

One of the unexpected findings was that feedstock availability, as posited in the literature review as an enabling factor, was revealed to also be an inhibitor in certain circumstances.

Some aspects of technological readiness were also found to be inhibiting rather than enabling. However, the consensus was that technology was ready from an infrastructure perspective but not necessarily from skills and knowledge perspective.

Respondents revealed in almost all cases that biogas dissemination is a case-by-case basis solution, where the nuances of the development of a project such as feedstock security, technology application, and saleability of digestate emerged as key factors for the success of each case.

Lastly, environmental security and its associated factors was cited as a grossly underestimated enabler because it is not necessarily quantified or factored into an electricity pricing model. As such, biogas is not fairly compared when alternative cheaper energy solutions are considered.

In conclusion, the results presented offer clear guidance in identifying and understanding both enablers and inhibitors of the successful implementation of commercial biogas in South Africa.

CHAPTER 5. DISCUSSION OF THE RESULTS

5.1 Introduction

The previous chapter provided a detailed narrative of the perspectives of the respondents offer about the research instrument and in turn the research propositions. Salient results were coded against the main research propositions and are now discussed in this chapter about the literature review, presenting the opportunity for validation of the research. A summary of the salient heuristically significant aspects of this research is provided and allows the opportunity for explanation and synthesis of additional ideas or arguments.

The discussions are placed into the relevant categories concerning research proposition 1 or research proposition 2 (broadly being responses relating to enabling and to inhibiting factors respectively). Sub-headings have been carried through from the results section to allow for comparative review and discussion of the literature review.

5.2 Discussion pertaining to research proposition 1

5.2.1 *Energy security*

The literature review referred to the concept of energy security as a critical emerging topic internationally, notably as published by the World Economic Forum. Of the six criteria used to evaluate energy security on a qualitative and quantitative basis, respondent contributions were categorised into the economic sectors of agriculture, municipal and industrial. Emergent in all three sectors was the concept of energy security. Specifically, three of the criteria had recurring themes congruent with respondent data as coded into the categories suggested by the World Economic Forum (2016a):

1. Self-sufficiency and diversity of supply;
2. Infrastructure resilience and flexibility;
3. Economic risks and increases in demand.

To be able to confirm the improvements in energy security in the three means described, the process of the AD and the uses of biogas discussed in the literature review have been tested during the research process. Respondents conclusively affirmed their support for the benefits of biogas as either a thermal fuel or electricity generation means. Some respondents also indicated the potential for building a gas-grid in South Africa as an alternative to electricity generation.

Based on respondents' perspectives across agriculture, municipal and industrial sectors, the most prominent findings were as follows:

Self-sufficiency and co-related economic risks of electricity price increases by the South African utility were main drivers and thus enablers for the increase in dissemination and speculation of further increases in the future. In particular, the potentially increased self-sufficiency and realisable economic benefits for municipal WWTP appear the most significant.

Benefits of AD adequately incorporated into sizeable municipal WWTP systems as reported by respondents are summarised as follows:

- Increased effectiveness of de-nitrification (an essential requirement of the wastewater and effluent treatment process);
- Increased overall efficiency of the WWTP and resultant capacity increase leading to lower requirements for upgrades and expansion;
- The utilisation of captured biogas to heat digesters, particularly in the colder Highveld areas, would increase the AD efficiency significantly and allow the production of more gas and digestate than the standard cold digestion process;
- Better performance of WWTP against their targets for environmental emissions including target COD, BOD and in future, methane or GHG emissions;
- Employing generators or CHP to produce electricity from biogas will represent a long-term investment in securing self-sufficiency of electricity which could lead to lower overall operational costs, backup power if not

wholly dependent on the electricity grid, and protection from substantial electricity price increases;

- Larger municipal WWTP receives a combined effluent of wastewater – both sewage from human use, stormwater and industrial wastewater.

Respondents cited the agriculture sector in South Africa, particularly the more significant agro-industrial farming operations as prime candidates for benefit from biogas dissemination. Energy security emerged as a theme once again, with benefits given by respondents in the South African context summarised as follows:

- Insofar as disposal of condemned and hazardous waste such organs and blood produced by abattoirs, the economic benefit of either self-digestion or sending the waste to a centralised biogas digester was seen as significant. The significance from an energy security point of view would be realised by the lower or removed need for expending thermal or electrical energy in the pre-processing or pasteurisation processes required by these industries before disposal. If own disposal is not done and landfill is used, then the benefits would be in the transport costs and savings from landfill gate fees;
- AD systems run at abattoirs would provide electricity and thermal energy for the abattoir representing a long-term cost saving from an energy perspective, a buffer against electricity price increases, and self-sufficiency in the case of remote areas;
- Farmers producing a consistent amount of animal manure such as piggeries, dairy farmers and cattle feedlots would derive economic benefit from either using their waste stream for own energy production or selling this on for a centralised biogas producer to provide electricity and digestate at a lower cost.

Industrial sectors have already benefited from increased energy security such as the sugar industry from the use of bagasse to produce electricity. Some respondents have described the further realisable energy security benefits in the industry and in the literature, where wastewaters from beer brewers, pulp and paper industry and petrochemical industry is beneficiated for biogas due to its high COD content. Enablers are thus summarised as follows:

- AD as a means of wastewater/effluent treatment while producing biogas as energy fluid decreases the need for advanced, energy-intensive processes;
- Thermal use of biogas to replace natural gas or coal on boiler systems to produce steam is a significant energy saver and decreases reliance on external fuels and electricity from the grid;
- Energy-efficient CHP engines maximise the calorific value of biogas from wastewater and represent an efficiency-enhancer over rudimentary electricity from coal-fired power stations and grid electricity.

5.2.2 *Environmental security and sustainability*

Most respondents were in a position to comment on the environmental impact of biogas processes, and these perspectives were offered separately from experts in agriculture, municipal and industrial sectors.

Responses indicated that biogas processes are unequivocally beneficial to the environment in considering the life cycle of the process. Their views supported the findings by Holm-Nielsen et al. (2009) and Boulamanti et al. (2013) in respect of biogas' lifecycle impact and its ability to reduce the agricultural load on the environment. The mitigation of methane emissions by the treatment of animal manures in particular, such as cattle feedlots, stood out as a primary feedstock for a prominent South African biogas plant.

A factor not necessarily covered directly in the literature review was that the significant greenhouse gas potential of untreated or unflared methane produced in agriculture and municipalities, and supported the findings made by Jorgenson (2006) and Ravindranath (2006).

Environmental security was discussed in the literature review concerning the shortfalls identified by the Yale Environmental performance index, which holds significance for the importance of the environment and its sustainability for the future of any economy, the most significant aspects were:

1. Agriculture
2. Climate and energy
3. Air quality
4. Air pollution
5. Water and sanitation

The aspects covered in the index are conceptually covered in the various Acts of Parliament of the Republic of South Africa, as shown in the literature review, and in particular, the considerations promulgated by the National Environmental Management Act and its various amendments such as the Waste Act, Air Quality.

Views were converging on the clear environmental benefits of agricultural, industrial and municipal waste abatement. Respondents also emphasised the importance of waste management schemes and the performance of biogas processes; if the biogas life cycle is not adequately managed, then the environmental benefits are reduced.

5.2.3 *Feedstock availability*

As cited in Republic of South Africa (2003), the agricultural organic residues and wastes are relatively abundant, which was confirmed by several respondents, and across all sectors including municipal and industrial.

However, respondents indicated that while feedstock is available, it needs to be secured diligently and becomes the deciding factor for the success or the failure of a biogas project. Feedstock security was succinctly described by a respondent as being more than just availability:

- Availability and proximity to feedstock;
- A consumer of electrical energy or thermal energy;
- A secured off-taker of digestate.

Several respondents confirmed the fact that many developers did insufficient due diligence as having a detrimental effect on the viability of a biogas project; without feedstock, biogas and digestate cannot be consistently produced and affects the viability of such as an operation. A further complication identified by respondents is that the nature of an AD in biogas is biological which lends itself to long system response times and inability to cope with tremendous system upsets.

5.3 Discussion pertaining to research proposition 2

5.3.1 *Regulatory frameworks for biogas*

The literature review explored, among other things, the inception of the renewable energy and sustainable energy resources document for South Africa, the White Paper on Renewable Energy (2003). Respondents indicated that there is still today, little or no supportive regulatory frameworks tailored explicitly for the commercial biogas industry in South Africa. The consideration of the REI4P (which was promulgated in 2011), was intimated in the literature review where the question was posed whether REI4P made sufficient allowance for biogas and why there was no uptake of biogas projects in the various REI4P bid windows. The purpose of the REI4P was to introduce 18 GW of electricity from renewable resources into South Africa's grid (Walwyn & Brent, 2015).

Respondents indicated that the REI4P was a successful and sophisticated programme that favoured renewable energy. Unfortunately, biogas' value proposition was not adequately quantified because firstly, the environmental benefits were not demonstrated. For example, as indicated by several respondents, solar PV and wind power as renewable energy sources directly harness energy from the environment and produce cheap electricity, yet there is no waste abatement or real greenhouse gas reduction benefit as with biogas.

Further perspectives from respondents revealed a two-fold issue concerning regulation: uncertainty where biogas is positioned in regulation, and secondly, the ineffective enforcement of current waste management regulations such as the NEMA and its Waste Act.

Several respondents mentioned the extent to which municipalities do not adequately enforce the waste management policies that exist in the South Africa legislation. One respondent indicated that in some instances the municipal landfill sites might compete with the potential dissemination of biogas as waste abatement method; the primary objective for municipalities would be to avoid, then to reduce and then treat wastes – in practice, this is not so at present.

5.3.2 *The infancy of the biogas industry*

Respondents noted that the perceptions of both investors and potential biogas producers are still subject to industry bias, whereby the failure of one project for whatever reason affects the whole industry. As discussed during the literature review the underlying mechanisms that would enable or inhibit the implementation of biogas were discussed and not simply a cursory analysis of the economics of projects. The acceleration of the biogas industry in South Africa has only really gained momentum since 2015 when the Bronkhorstspruit biogas plant (4.6 MW capacity) was commissioned. Several factors such as the robustness of the plant, but also the criticality of correct operation of the plant was emphasised. Furthermore, the ongoing supply of digestate as an organic fertiliser has, according to some respondents, created more interest for detailed inquiry in the biogas industry.

It became apparent from respondents that the expected time frame for a return on investment in the biogas industry is generally longer than with competing renewables or other infrastructure projects. The education and expectation management deficiency of investors and developers in respect of economic returns is important and would likely improve as more larger scale projects are built successfully.

Respondents that offered a technical perspective on the design and construction of biogas plants noted the lack of knowledge economy and absence of a South Africa-specific knowledge base for biogas. Respondents suggested biogas-specific standards for construction and operation of these plants.

Lastly, it appears the infancy of the industry could be the effect of lagging knowledge from supportive structures and a lack of appropriate incentives and regulatory frameworks.

5.3.3 *Competition from alternatives*

A factor that was not postulated in the literature review but regularly revealed in respondent perspectives was the presence and cost advantages of alternatives to biogas. For example, as described by respondents, it is cheaper to buy electricity from Eskom than to produce it from biogas. If one had to incorporate a renewable technology, then technologies on the large scale such as wind power and solar power are substantially cheaper than electricity from biogas.

However, the environmental benefits as enablers for biogas are ignored or underestimated when only considering price of electricity. The additional benefits of biogas in terms of digestate, water management, odour reduction, pathogen mitigation does not always have a quantitative measure assigned to them.

Furthermore, alternative waste disposal methods such as landfill, composting or dumping, occur frequently particularly due to low levels of enforcement of the laws by municipalities. Industrial operations

5.4 Conclusion

The discussion of results vis-à-vis the literature review provided emergent themes which crystallised and triangulated respondent perspectives into a few heuristically significant points that pertain to each research proposition and in turn, research question with its sub-problems.

Bearing a paradigm of energy security as posited in the literature review – being enablers for biogas in South Africa, the respondent perspectives were undoubtedly decisive in affirming the underlying mechanisms that contribute to these factors as discussed in the literature review.

Environmental security enhancements, specifically in terms of the benefits derived by responsible waste abatement and mitigation, were affirmed by respondents as significant contributors to enabling biogas dissemination in South Africa.

Respondents concurred with feedstock availability, and technological readiness insofar as municipal and industrial sectors are concerned, but regarding the same for agriculture identified a challenge. The aspect of feedstock availability in agriculture is problematic, however, was an unexpected materiality that presented a somewhat nuanced finding for feedstock security. The finding does not necessarily present a direct inhibitor for biogas implantation, but its importance should not be ignored nor underestimated by stakeholders in the industry.

In conclusion of Chapter Five, the discussion has highlighted the convergence of the results obtained from the research instrument with aspects of the Literature Review herein. The discussion provides the basis for understanding the most important factors for successful commercial biogas implementation in South Africa.

CHAPTER 6. CONCLUSIONS & RECOMMENDATIONS

6.1 Introduction

The closing chapter of this study presents the salient and most heuristically significant conclusions derived from the research process and aims to relate this back to the research propositions. Prima facie recommendations of significance are presented to stakeholders interested in the research topic, and this is further extended by positing broad suggestions for further research and inquiry.

6.2 Conclusions of the study

This study concludes that the enablers for biogas implementation in South Africa, after having consulted South African stakeholder perspectives, are the energy security and environmental security potential offered by the dissemination of biogas. Increased energy security would be realised through energy savings on waste disposal, use of biogas as a thermal fluid or to produce electricity. Increased environmental security would be realised in biogas' ability to process waste and by-products that would otherwise negatively affect various aspects of the environment.

The positioning of biogas is perhaps more adequately suited as a non-distributed solution. The project-specific nuances of feedstock security, digestate saleability and the ability to understand the environmental benefits that are not always straightforward, are required to evaluate a project and determine its success or failure.

The trend globally, and locally, of renewable energy incorporation into the energy mix offers opportunity for biogas to become part of that mix. However, biogas at a larger scale is currently at its infancy and could be boosted by stronger regulations and enforcement in terms of organic waste management in the agriculture, municipal and industrial sectors.

6.3 Recommendations

Stakeholders in the biogas industry in South Africa and greater sub-Saharan Africa may appreciate findings made by this research. Because a diverse group of respondents were selected using purposive sampling technique, perspectives span across all relevant identified sectors concerning biogas. Respondents interviewed represent a key, experienced professionals with a non-myopic view of the industry.

The business case for biogas rests upon the underlying technical and commercial factors, which do not necessarily contribute equally to each particular project. Broadly, recommendations are made for the type of stakeholder and are arranged per industry sector.

6.3.1 *Recommendations to agriculture*

South Africa's agriculture sector is comprised of many large-scale farmers which either use vertical integration techniques in their businesses or not. Concerning biogas, it is useful to consider their organic waste streams as a starting point for feed.

As demonstrated in this research, the business case for biogas in agriculture depends firstly on the type and scale of waste/by-product produced. In an ideal world where agriculture adheres to all existing waste disposal regulation and the enforcement of these regulations is up to standard, the requirement for biogas as a waste mitigation method becomes clear.

High-intensity farming such as piggeries, cattle feedlots, dairies, and chicken farms produce highly concentrated waste streams that negatively impact the environment regarding odour, pathogens and water quality. Abattoirs and slaughterhouses have an even more prominent and noticeable effect. Concentrated waste streams provide solid feedstock for biogas.

Secondly, the critical factors for the success of an agriculture biogas plant are:

- Proximity to feedstock;

- Secured feedstock with due diligence completed;
- Off-taker of digestate;
- The user of the energy (electrical or thermal).

Medium-to-large scale operations of this nature can benefit from the installation of biogas plant. The main effects would be:

- Additional energy generation;
- Self-sufficiency from the grid and protection against utility electricity price increases;
- Lowered or eliminated costs of waste disposal to landfills or hazardous waste facilities;
- Improved public perception.

6.3.2 *Recommendations to industrial operations*

Research showed that, globally, industrial operations such as large breweries are already employing some scale of biogas on their sites and have derived benefits from that place. The case has been demonstrated in South Africa as well as scope for more utilisation.

Industries which produce food by-products or animal by-products that are traditionally disposed of could employ small biogas facilities to process this waste safely and produce additional energy.

Main effects would be:

- On-site processing of food waste;
- Minimised storage and stockpiling of waste;
- Additional energy security;
- Decreased odour and pathogen risk;
- No transport costs to further external processing;
- Decreased municipal wastewater tariffs/discharge fees.

The industry is additionally poised to integrate such a process into their facilities and benefit from their existing engineering and skills infrastructure.

6.3.3 *Recommendations to municipalities*

The municipal wastewater treatment plants in South Africa are existing infrastructure that already employs a type of biogas digester in its process. Significant municipalities have been shown to be constrained with increasing electricity costs. Municipalities should begin with their most extensive facilities and consider upgrades or modifications to capture the biogas produced from the cold digesters; raw biogas should be used to heat the digester subsequently. The increased temperature would increase the overall efficiency of the WWTP due to better reaction rates and higher capacity for solid waste. The improved efficiency of the digesters may result in a lower requirement for overall capacity upgrades, demonstrating a cost saving without substantial investment.

Once digesters run more efficiently, more gas would be produced, and additional gas could be captured and used in CHP units to produce electricity. There are many large electricity consumers on such WWTP, and the municipalities would see an overall cost reduction and improved efficiency.

6.3.4 *Recommendations to policymakers*

When viewed against the existing policies for renewable energy and waste, which are matters of relevance for biogas, perspectives offered by South African respondents indicated rather conclusively that there is a lack of directed policy for biogas in the country. The inclusion of biogas in the REI4P was debated by respondents as being weak and inappropriate, and further unable to compete directly with other forms of renewable energy as distributed power solutions.

Although some advances were made in respect of waste management regulation and licensing requirements as a whole, the Waste Act is not prescriptive enough to stimulate the development of biogas in South Africa. Furthermore, the Fertiliser Act of 1947 is most likely due for a significant revision; the inclusion of digestate as an organic class of fertiliser into this Act could provide a stimulus for agriculture to adopt or include organic fertiliser. There is potentially an excellent opportunity for a digestate or organic fertiliser industry association, where collaboration with the government could provide free or subsidised organic fertiliser for community food projects.

The findings of this study suggest that to pursue biogas in utility-scale or similar distributed electricity network incentives and policies is perhaps the incorrect frame of reference. Instead, biogas should be separated entirely from renewable energy as an overall basket of technologies, as well as be removed from the “bio-energy” category into which biodiesel and bioethanol fall. Biogas could be repositioned into the waste management priorities by the already existing waste hierarchy. Biogas insofar as policy is concerned would:

- Eliminate or ban the disposal of organic waste onto landfills;
- Promote the economic and environmental benefits of hazardous waste pre-treatment or partial treatment using AD;

An additional point of investigation would be the adoption of micro gas grids in remote areas where biogas plants may be situated. A gas micro-grid could provide heating and cooking energy source for rural and subsistence communities which would otherwise not have had access to energy.

Another potential framing of biogas regarding policy would be to create more stringent industrial wastewater effluent discharge standards for industries, particularly those whose wastewater contains high levels of COD and BOD, which present feedstock for biogas generation. The alleviation of strain on the ecosystems and municipal wastewater treatment facilities would serve significant long-term benefits insofar as environmental management and sustainability are concerned.

6.3.5 *Recommendations to project developers*

Project developers for biogas in South Africa would include the entire team of financiers, investors, technology suppliers and the end-user interface. A consideration that emerged strongly from the research was that the economic analysis of a biogas project firstly does not consider the environmental benefits in a quantifiable way. Secondly, there appears to be a lack of engagement of project developers with the biogas technology in that the return on investment expectation horizon differs vastly from other renewables projects.

6.4 Suggestions for further research

The exploration of the topic of biogas was intended to be broad but with specific reference to South African context. The topic has a diverse sample of respondents; holistic perspectives were offered by respondents, which during analysis and discussion has raised exciting ideas for further research that may be of significance at present day. The suggestions span social, economic and technological fields.

6.4.1 *Valorisation of digestate*

Respondent 1 briefly touched on the aspect of upgrading the economic value of digestate produced by anaerobic processes, explicitly concerning the urban wastewater treatment sector. Research abroad is underway which considers the tertiary processing of digestate into succinic, malic, and propanoic lactic acids which have substantially higher economic value than digestate itself.

It is potentially the case that digestate valorisation into these products could represent increased value propositions for anaerobic digestion uptake in South Africa. The sugar industry, for example in South Africa, Swaziland and Mauritius, produce tertiary value-added products from sugar such as potable ethanol and furfuryl alcohol. This type of innovation has protected the sugar producers from price inflation and world supply and demand changes. It could be posited that valorisation of digestate would present the same value proposition for all anaerobic digestion processes in the agriculture, industrial and municipal sectors.

According to Respondent 1, the current horizon for establishing this type of valorisation process is several years due to a lack of substantial current research. Valorisation of waste from a wastewater treatment plant or landfill is particularly useful when the waste cannot be used for any other economic reason, and therefore if beneficiated can provide a benefit.

6.4.2 *Impact of increased renewable energy uptake on fossil-fuel power prices*

Respondent 2 noted that bankability of large energy projects such as electric power producers is contingent on finance which in turn is dependent on insurance programmes being in place. Increasing trends towards renewable energy and its significant uptake in South Africa owing to the successes of the REI4P between 2011 and 2014, has moved investors and large multi-national insurers to re-evaluate their position on project risk. Severe cost and timeline overruns as experienced with Eskom's Kusile and Medupi power stations have impacted the insurance profile and perceptions towards coal; this impact decreases the number of players in the market who would insure the construction and maintenance programmes of these projects. In turn, prices increase and ultimately reflect the nett cost per kilowatt-hour of electricity.

6.4.3 *Social perceptions of biogas from sewage treatment plants*

Several respondents as well as the literature reviewed (but not necessarily incorporated into this work), indicated that biogas could be used without upgrading, in communities as a cooking and heating energy source as is the case in China and India's rural areas. In South Africa, biogas digesters in small communities or those relatively close to wastewater treatment works could provide an energy source. The social perception of cooking and even heating water with gas derived from municipal and sewage waste in South Africa may impact, possibly detrimentally, the uptake thereof, no matter how viable.

6.4.4 *Biogas process integration into other bio-energy processes*

The potential of increased usage of biogas at wastewater and industrial processes has been discussed in the research, however, what could further be explored is the viability of the integration of anaerobic digesters into processes that are relatively new in South Africa. These processes, for example, could be

6.4.5 *Effects of inadequate enforcement of regulation on waste management*

Regulations in respect of solid waste to landfills and liquid waste to municipal effluent in South Africa do exist, but several respondents questioned the enforcement thereof. Specifically, in rural areas, if enforcement is not reliable, then there is a tendency for industrial and agricultural producers to dispose of their waste in the cheapest way possible. There are environmental consequences of illegal disposal methods which include water supply contamination, river pollution, groundwater contamination, irrigation-related runoff and contamination, odour issues, pathogenic issues relating to soil and water and many others.

6.4.6 *Knowledge economy for biogas processes*

Respondent 8 touched on his experiences of industrial wastewater treatment using anaerobic digestion and indicated that even within the large multi-national company, there are stark differences in opinion and methodology on how to efficiently run these plants. It is potentially valuable to investigate the knowledge economy that exists around running a biological process such as anaerobic digestion and to produce a best-practices guide. Quantification and comparison of economic and environmental benefits derived from each facility could set the stage for policy development, incentives and financing motivation for the industry at large.

6.4.7 *Biogas and microalgae integration*

Respondent 9 suggested the potential for integrating microalgae growing farms into biogas facilities to clean the biogas. Algae absorb carbon dioxide in the biogas as well as some of the sulphur compounds. The product gas can then be directly used in a standard CHP gas engine instead of unique biogas engines, which represents a cost benefit. In this closed system, algae produce oil, which is pressed from the algae. The residue which remains is then pelletised and either fed to cattle or used as feed for the biogas plant.

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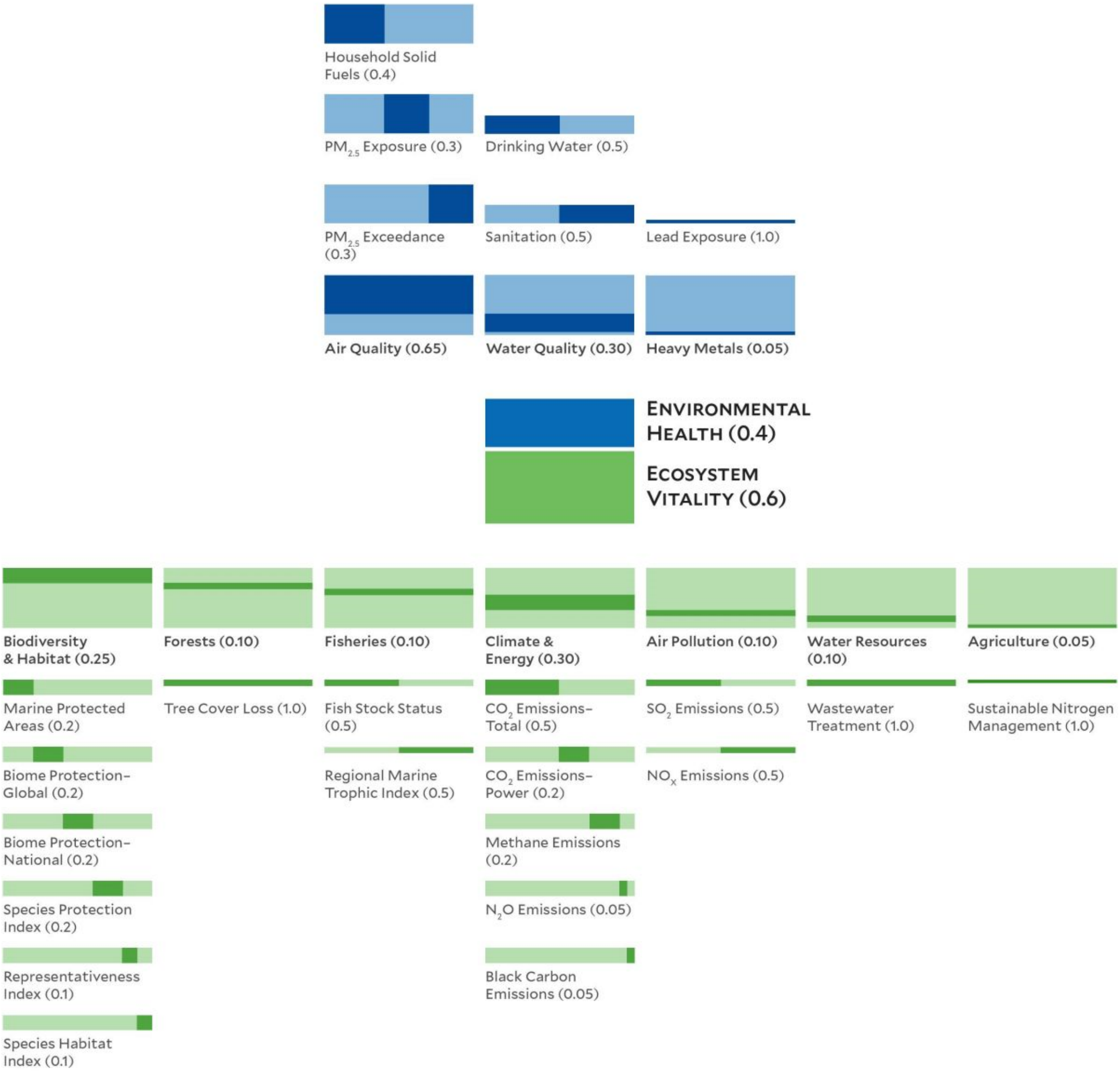
APPENDIX A

No.	Research instrument: semi-structured interview schedule
1	How do you perceive biogas in South Africa at present day?
2	Do you think that biogas has been adequately considered in the NDP, IRP and REIPPPP?
3	Would anaerobic digestion products be of use to agriculture in South Africa?
4	Would anaerobic digestion products be of use to industry in South Africa?
5	What do you say are the main barriers to biogas dissemination in South Africa?
6	Considering our municipal infrastructure, do you think biogas is a viable “bolt-on” technology for wastewater treatment facilities?
7	Do you think that biogas production benefits the environment overall and if so how is it measurable?
8	Can biogas provide a greenhouse gas or carbon mitigation contribution?
9	Do you think that an appropriate incentive for industries to produce biogas could be developed? If so, elaborate?
10	Do you think it is possible or practical for South Africa to produce electricity from biogas and feed it to the grid or rather use it for heating?
11	What are your thoughts on the technological readiness of South Africa for biogas?
12	What are your thoughts regarding the social perceptions and potential impacts on communities regarding biogas?

APPENDIX B



Household Solid Fuels (0.4)
$PM_{2.5}$ Exposure (0.3)
Drinking Water (0.5)
$PM_{2.5}$ Exceedance (0.3)
Sanitation (0.5)
Lead Exposure (1.0)
Air Quality (0.65)
Water Quality (0.30)
Heavy Metals (0.05)
ENVIRONMENTAL HEALTH (0.4)
ECOSYSTEM VITALITY (0.6)
Biodiversity & Habitat (0.25)
Forests (0.10)
Fisheries (0.10)
Climate & Energy (0.30)
Air Pollution (0.10)
Water Resources (0.10)
Agriculture (0.05)
Marine Protected Areas (0.2)
Tree Cover Loss (1.0)
Fish Stock Status (0.5)
CO_2 Emissions–Total (0.5)
SO_2 Emissions (0.5)
Wastewater Treatment (1.0)
Sustainable Nitrogen Management (1.0)
Biome Protection–Global (0.2)
Regional Marine Trophic Index (0.5)
CO_2 Emissions–Power (0.2)
NO_x Emissions (0.5)
Biome Protection–National (0.2)
Methane Emissions (0.2)
Species Protection Index (0.2)
N_2O Emissions (0.05)
Representativeness Index (0.1)
Black Carbon Emissions (0.05)
Species Habitat Index (0.1)