SARChI TRANSFORMATIVE INNOVATION, 4IR AND SUSTAINABLE DEVELOPMENT

UNIVERSITY OF JOHANNESBURG

A policy and innovation perspective on micro-digesters in South Africa

A report to UJ-PEETS as part of a project to review industry status and develop a sector development plan

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Executive summary

Anaerobic biogas digesters have the potential to provide communities with alternative energy sources through the transformation of waste material (e.g. cow dung or food waste) into gas. This gas can be used for cooking, lighting, heating or turned into electricity. It, therefore, provides the opportunity for cleaner cooking, lighting and heating energy where firewood or charcoal, for example, is used. It also has the potential to provide electricity where access to grid-electricity supply is unavailable or unaffordable. They have the benefit of managing waste decomposition, reducing the need to send organic waste to landfill reducing methane emissions. In addition to gas, biogas digesters also produce an organic substate that can be used as fertiliser. Finally, biodigesters' building, operating, and maintaining is labour intensive and therefore provides opportunities for employment creation. As such, anaerobic biogas digesters have been promoted as a viable waste to energy vehicle with more comprehensive economic benefits for communities and businesses.

Sanedi has commissioned the University of Johannesburg's Process, Energy and Environmental Technology Station (UJ-PEETS) to take stock of the current status of micro-digesters and the wider state of the art (in South Africa and globally). For this study, micro-digesters have been classified using the South African National Energy Development Institute (SANEDI) definition as "digesters that fall below the minimum licencing and permit requirements from various government departments."

The DST/NRF/Newton Fund Trilateral Research Chair on Transformative Innovation, the Fourth Industrial Revolution and Sustainable Development at UJ (UJ-TRCTI) has been requested by UJ-PEETS to provide a series of inputs to assist them in conducting the feasibility report and the development of the sector development plan for these micro-digesters.

This report is based on a wide-ranging literature review and several stakeholder engagements between October 2020 and March 2021. The report outlines an analysis of the South African micro-digester sectoral innovation system and finishes with a series of recommendations. It also concludes with a proposed process for developing a sector development plan, the completion of which we argue is the appropriate next step should stakeholders agree to continue to promote the micro-digester biogas sector in South Africa. It is not possible to develop a sector development plan at this time due to the level of stakeholder engagement needed and which was not possible in 2020-early 2021; in part related to the COVID-19 pandemic restrictions at that time. This executive summary focused on the recommendations and proposed next steps that arise from our review.

The innovation systems approach is a relevant lens for those thinking about invigorating the micro-digester sector in South Africa through a sector development plan because it focuses on breathing new life into the country's economic activities. It recognises all actors involved in the micro-digester space and focuses on long-term viability and economic sustainability and its links to social and environmental sustainability. A sectoral approach recognises that actors within the system are influenced by, and influence, the technology and knowledge in the system. These, in turn, are influenced by the strength of networks. The *linkages* between each of the elements (their strength and focus) determine the success of a sectoral innovation system. Furthermore, a set of (dis)enabling institutional factors are key to the system's success.

The study of the micro-digester sector in South Africa found that there are established technologies (micro-digester designs) being used in South Africa but are not economical compared to other cooking and electricity technologies. Our techno-economic analysis found the results for levelized cost of energy and levelized cost of cooking, even in what are seen as high performing micro-digesters, to be between 1.5 and 4 times as expensive as grid electricity or bottled LPG gas. The study also found that there are potential market segments that have not been thoroughly investigated for micro-digesters. Furthermore, examples from other countries highlight the opportunity for value addition beyond cooking – where most projects focus attention in South Africa. As a result, there are opportunities for a business model and organisational innovation in the sector.

RECOMMENDATION 1: Move the narrative beyond energy and cooking to bring in the benefits from other value addition available from using a micro-digester especially waste management and fertiliser from digestate. This requires agreement by sector stakeholders as to who's role it will be to promote this broader value addition perspective. The obvious candidates for this role are Sanedi and SABIA.

RECOMMENDATION 2: Encourage business model innovation (e.g. Pay-as-you-go or payment in instalment schemes; sales of gas produced being bagged or bottled for sale to the surrounding community as clean cooking; charging of batteries, lights and mobile phones using biogas generator) and organisational innovation, especially community-based biogas micro-digester schemes.

The UJ-PEETS industry status report found that private business actors are involved in this sector and supported by an industry lobby group. However, the industry is currently dominated by development partners, and government subsidy schemes focused on rural consumers. This is at the exclusion of potential market segments in urban areas (where most of the population live). These require portable and/or modular systems and potentially more community-focused schemes that may need to be slightly larger than those currently being promoted to rural homesteads and community facilities. They also require incentive schemes to encourage more innovation in this sector.

RECOMMENDATION 3: Conduct more research in collaboration with the private sector. This needs to focus on foresight research to understand changing market trends. More market segment analysis is also necessary to understand the potential opportunities (especially in urban environments) and possible models for community-sized systems.

RECOMMENDATION 4: Enhanced demand-pull financial incentive schemes (e.g. innovation competitions) to stimulate private sector interest and public-private partnerships in this sector.

Institutionally, policy support is insufficient due to the limited focus on biogas in the context of bioenergy and biofuels. The focus of policy support has been on industrial scale biogas. The interest in dealing with the growing levels of urban waste (illustrated by one province's move towards eliminating organic landfill waste) provides a window of opportunity for increased policy coherence.

RECOMMENDATION 5: Develop dedicated biogas policies and support legislation by relevant government ministries to enable innovation in the sector. This includes clearer standards and policies to incentivise finance options and training. The guidelines to plan and implement the anaerobic micro digester projects in South Africa need to become more accessible and promoted more widely. This will assist industry and the sector more broadly to segment the market and develop strategies to develop the sector.

To move these recommendations forward, we recommend two immediate next steps. The first is to finalise a theory of change through stakeholder engagement, particularly with the private sector. A sector-level theory of change allows organisations within sectors to advocate for their work more coherently; focuses attention on where impact is needed and continuity of activity across the sector. This is particularly important in a sector where we can see the need for more effective market segmentation. Following this, we recommend further development of a sector development plan. A sector development plan is a physical document that outlines the steps required to move an industrial sector from infancy to maturity. It provides a roadmap for the promotion of the recommendations outlined here and should be conducted with stakeholder engagement also

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Background

Anaerobic biogas digesters have the potential to provide communities with alternative energy sources through the transformation of waste material (e.g. cow dung or food waste) into gas. This gas can be used for cooking, lighting, heating or turned into electricity. It, therefore, provides the opportunity for cleaner cooking, lighting and heating energy where firewood or charcoal, for example, is used. It also has the potential to provide electricity where access to grid-electricity supply is unavailable or unaffordable. They have the benefit of managing waste decomposition, reducing the need to send organic waste to landfill reducing methane emissions. In addition to gas, biogas digesters also produce an organic substate that can be used as fertiliser. Finally, biodigesters' building, operating, and maintaining is labour intensive and therefore provides opportunities for employment creation. As such, anaerobic biogas digesters have been promoted as a viable waste to energy vehicle. In several countries (e.g. China, Bangladesh, Brazil or Kenya and Tanzania in Africa), this technology has been taken up – especially at the small or micro scale size. China has the largest number of installed small-scale biogas digesters, standing at over 45,000 (Mathias, 2014). In Africa, the numbers are smaller – Kenya, for example, has over 14,000, Uganda 11,000 and Ethiopia 10,000 (IEA, 2020). The total number of biogas digesters installed in South Africa is estimated to be in the region of 700 of all sizes (Muvhiiwa et al, 2017).

Biogas digesters come in a range of sizes. This report is focused on micro-sized anaerobic biogas digesters (herein referred to as 'micro-digesters'). It is defined by the South African National Energy Development Institute (SANEDI) as "digesters that fall below the minimum licencing and permit requirements from various government departments" (Sanedi, 2017). There is no standard definition of what size such digesters are in South Africa. Micro-digesters, are typically 5 to 15 m^3 in volume with a gas output of 0.5 m^3 per m^3 of digester volume (Mutungwazi et al., 2018; Bond and Templeton, 2011). This output is equivalent to 3.2 kWh gas per m^3 per day. That said, anecdotal evidence received during this study informed us that many in South Africa see micro-digesters as anything up to 100m^3. A USAID document (dated 2020) on anaerobic biodigester project guidelines developed with guidance from the National Biogas Platform's micro-digester working group outlines that a micro-digester is classified as producing less than 0.5kw of power or less than 2kw of biogas a day for household use.

Approximately 50% (approximately 350) of South Africa's biodigesters can be classified as 'micro' in size (Muvhiiwa et al, 2017). Around 100 of these have been supported by Sanedi's Working for Energy programme since 2014. They are located in Gauteng, KZN and Limpopo and operate in schools, early childhood development centres and individual homesteads/ farms.

Sanedi has commissioned the University of Johannesburg's Process, Energy and Environmental Technology Station (UJ-PEETS) to take stock of the current status of these micro-digesters and the wider state of the art (in South Africa and globally). In so doing, UJ-PEETS was tasked to:

- Conduct a feasibility report listing identified gaps and recommendations on creating awareness, education and training to develop the micro digester industry in South Africa further
- Develop a sector development plan
- Promote further collaboration between all parties during the implementation of the sector development plan

The DST/NRF/Newton Fund Trilateral Research Chair on Transformative Innovation, the Fourth Industrial Revolution and Sustainable Development at the University of Johannesburg (UJ-TRCTI) has been requested by UJ-PEETS to provide a series of inputs to assist them in conducting the feasibility report and the development of the sector development plan.

The material for this report has been generated from:

- A thorough desk review of materials relating to the biogas industry in South Africa and sub-Saharan Africa more generally. This desk review was conducted using an internet search using keywords in various combinations of: 'micro', 'bio', 'anaerobic', 'digester', 'South Africa', 'Africa'. This was complemented by a targeted search of relevant websites, including Sanedi, SABIA, core industry firms, and international development partners. This was further supplemented through snowballing of references found during these searches and/or referenced during workshops. A review of innovation systems literature on similar technologies, e.g. briquettes or technologies with similar behaviour change requirements, e.g. clean cook stoves.
- A small theory of change workshop was held in February 2020 with academic stakeholders and Sanedi representatives. The total number of participants attending from outside UJ-TRCTI was 10.
- A stakeholder and innovation system mapping exercise was conducted with a limited number of academic stakeholders and Sanedi representatives in March 2021. The total number of participants attending from outside UJ-TRCTI was 6.
- Three formal discursive multi-stakeholder meetings with various Sanedi staff and project managers involved in Sanedi funded projects in Gauteng and Limpopo between February and March 2021. These meetings focused on the experiences of the project activities to date, challenges and windows of opportunities encountered, and general reflections of attitudes to, barriers, and enablers for micro-digesters in South Africa. The number of external participants engaged across all three meetings was 18.
- A review of additional material and fieldwork conducted by UJ-PEETS as part of this project, notably the July 2020 Action Dialogue Report; the fieldwork results from UJ-PEETS review of biodigesters in Gauteng, Limpopo and Kwa Zulu Natal that took place in April 2021 and, the industry status report.

This document presents the results of this analysis in the form of a report with several annexes. The report outlines an analysis of the South African micro-digester sectoral innovation system. It also outlines the implications for policy of the findings of the innovation system analysis. The report draws on material from a range of studies that were carried out for this report, which are provided as individual annexes. The report finishes with a series of recommendations. It also concludes with a proposed outline of a sector development plan, the completion of which we argue is the appropriate next step should stakeholders agree to continue to promote the micro-digester biogas sector in South Africa.

Rationale for micro-digesters: a theory of change perspective

This report has been developed from a normative perspective that there is a role that micro-digesters can play in South Africa. Specifically, we start from the notion that micro-digesters can solve the following four problems:

- **Local variations in energy access and clean cooking**

  While energy access is high in South Africa (>90% - World Bank, 2021), this hides significant local variation and a high level of energy poverty. Access to grid electricity does not automatically mean people can afford to use electricity, while there are increasing issues with the quality of electricity provided by the grid due to current fluctuations and power outages/ load shedding. At the same time, many households and public facilities where cooking is conducted use multiple fuel sources for cooking (Ateba et al, 2018). Many still rely on firewood and/or charcoal which creates significant levels of indoor air pollution (Buthelezi, 2019).

- **Interconnectedness of water, energy and food**

  27% of all food in South Africa is wasted across the supply chain, and significant amounts end up in landfills contributing to over 4% of South Africa's greenhouse gas emissions (Oelofse, 2019). In addition, sanitation services and access to reliable and/or clean water are still low, especially in rural areas. More particularly, there is a need to recognise the interconnectedness of these issues and the broader 'water-energy-food nexus'. Micro-digesters can also provide a digestate or fertiliser source to support market gardens, vegetable and fruit production in schools, etc.

- **Lack of a sustainable micro-digester industry**

  Estimates place the number of biodigesters in South Africa at around 700 compared to around 10,000 in many East African nations and over 40 million in China. At the same time, in 2016 (latest figures available), there were estimated to be 1,700 jobs in the biodigester field in South Africa (Sagen, 2016); across all sizes of the industry as compared to 44,000 jobs in the whole of the renewables sector in South Africa (IRENA, 2019). The biogas micro-digester sector is not a large part of the renewable energy industrial sector. As a result, the sector lacks skills and capabilities.

- **Low levels of demand and awareness**

  There is a low level of awareness and demand for biodigesters relative to other renewable energy forms, cooking fuel, biowaste options and/or fertiliser. There are estimated to be only 700 biodigesters of all types and sizes in South Africa (Mutungwazi et al, 2018). However, the technology is suitable for at least 625,000 rural households based on livestock numbers and resulting organic waste to feed the digester (Rasimphi and Tinarwo, 2020).

Taking these problem areas as a starting point and based on a review of the literature and a 'theory of change workshop' held in February 2021, we have developed a proposed theory of change to ground this study (Annex 1).

Why a theory of change?

The 'theory of change' approach has developed from work on how to evaluate the impact of community initiatives (specifically realist evaluation approaches of Weiss, 1995). It sets out the building blocks needed to deliver on a programme goal through a pathway of interventions against a series of assumptions. It focuses on how working towards these goals leads to intermediate outcomes and how they are strategically important for ensuring the desired impact (goal) occurs. It is grounded in realist evaluation. It mainly focuses on the context – the current status of the problem being addressed and the underlying assumptions that will influence success or failure.

While predominately used in development programmes and across a wide range of public and non-profit organisations, it is starting to be used at a sector level (c.f. DFID, 2012 and Noble, 2016). Noble (2016) notes that a theory of change at a sector level can be useful for:

- Helping organisations within sectors to advocate for their work more coherently and consistently.
- Encouraging all sector players to think harder about how to deliver good services and make a difference.
- Providing a framework for organising the existing evidence base and identifying areas where evidence is stronger or weaker.
- Helping organisations and practitioners in the sector develop their own theories of change and evaluations of more specific programmes. This ensures continuity of activity

across the sector through nested theories of change, allowing more effective segmenting of markets and effective service delivery.

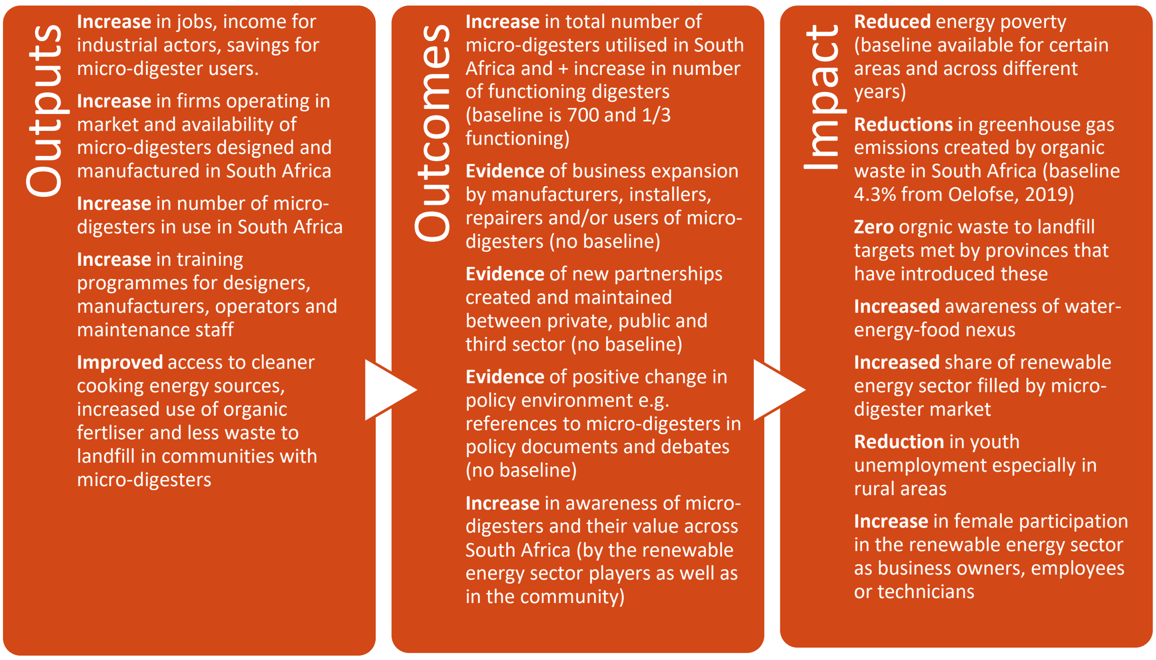
This last point is crucial for those looking for funding in the sector. Increasing development partners require theories of change in funding applications, and private finance investors are looking beyond traditional return on investment measures in their decision making (Eijck, 2019).

How we use the theory of change in this study

For the above reasons, this study starts by analysing the potential theory of change for the micro-digester sector. Annex 1 outlines the draft theory of change that has been developed as part of ongoing stakeholder engagement to review the micro-digester sector by Sanedi and UJ-PEETS. The theory of change was developed based on the initial findings of the studies conducted by UJ-PEETS for this project. A draft was developed in the first months of 2021 and underwent further refinement after a small stakeholder workshop in February 2021.

Below we summarise the proposed outputs, outcomes and impacts for the sector for a period proposed as between 2022 and 2026. Outputs refer to the tangible and measurable deliverables that are the direct result of sector actors' activities. Outcomes are measurable intermediate results created as a result of sector actors' interventions. Impacts are longer-term results that are less measurable or directly contributable to the effects of sector actors' interventions. Impacts are the desired end goals that will solve the initial problems that were the source of inspiration for the theory of change.

Figure 1: Key elements of the proposed micro-digester sector theory of change



It should be noted that Figure 1 and the complete draft theory of change in Annex 1 do not contain any specific target numbers and need finalisation of the timeframe in which change is to be measured. These (and the final agreed outputs, outcomes and impacts) must be agreed upon through a broader stakeholder engagement, particularly with members of the private sector who have been absent in many of these discussions that led to the development of this document. The Theory of Change thus requires further validation and finalising through further and more wide-reaching stakeholder workshops. Once the indicators have been agreed upon, a thorough baseline data collection exercise will be conducted against which progress towards the theory of change can be conducted as the sector development plan is implemented.

Key to a theory of change is the underlying assumptions that will determine the success or failure of activities to lead to change. The theory of change outlined in Annex 1 has been created based on the following high-level assumptions:

- The renewable energy sector remains high on the political agenda
- Industry players and others are keen to invest in new technologies, businesses and training
- Other cooking and heating fuels (e.g. LPG) do not become financially and logistically more readily available for key potential market segments that would benefit from micro-digesters
- There is continuing focus on the water-energy-food (WEF) nexus and the importance of systemic solutions to problems

These assumptions are discussed in more depth in the next section of the report.

The South African micro-digester sector innovation system

An Industry Status Report (Rasmeni, 2021) outlines the industry's status: available technologies and the challenges and barriers to their introduction. Along with Annexes 3, 4 and 5 of this report, they highlight that the micro-digester sector in South Africa is affected by few commercial sales and low demand. We have already outlined the low number of micro-digesters that are in use in South Africa (approx. 350 of the total 700 installed in the country), and many of these have been funded by development partners and/or government programmes. That said, there is a belief within the industry players that the technology is 'good,' i.e. the current designs can work well if they are correctly operated and maintained. However, due to the low levels of demand/ awareness of the technology, there are few suppliers of micro-digesters or significant numbers trained in their build, operation or maintenance. All of this occurs within the context of a high level of youth unemployment, policy maker awareness, and broad stakeholder buy-in to renewable energy (RE) issues. We also see an increasing understanding of the WEF nexus in policy discussions.

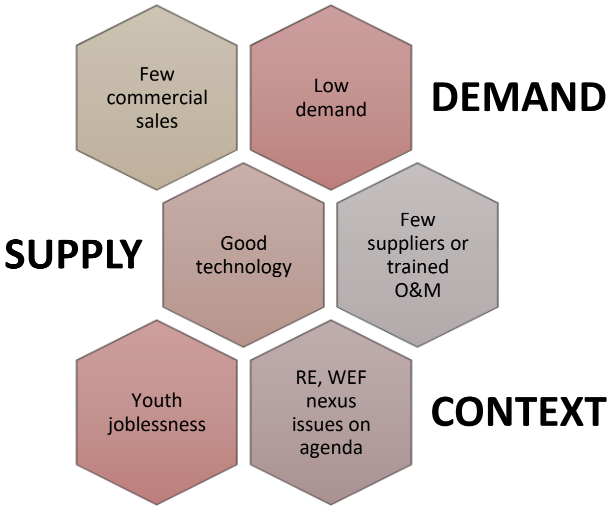


Figure 2: The micro-digester sector current status

Against this background, it is imperative to understand why the sector faces these supply, demand and broader contextual issues. One approach to doing this is from an innovation systems perspective.

The value of the innovation systems approach

Innovation is increasingly being recognised as essential for the growth of economies but also society more generally too. Innovation requires people to think differently and, when one person thinks differently, it gets others thinking differently, too. Innovation – in its broadest sense understood as the introduction of something new into an environment – has been widely recognised as essential for the economic development of countries worldwide. Innovation is promoted as a way to get firms doing things differently by introducing new products or processes into their business; to become more efficient and effective in their activities. The result is expected to be higher productivity growth, increased employment and – if targeted correctly – realising social outcomes (Booyens and Hart, 2019). Others have argued that it is possible to focus innovation on social and community activities. The concept of social innovation (c.f. Mulgan, 2012) has been proposed to meet the social need through new forms of collective action.

South Africa was the first African country to formally recognise this with its 1996 White Paper on Science, Technology and Innovation. The White Paper focused on building a 'national innovation system' or promoting the key building blocks that encourage and facilitate innovative activity. Taking an innovation systems approach focuses on the fact that innovation is a process. It is the collaborative activity between multiple actors that leads to the development and introduction of a new or improved product, process or organisational approach into a new environment. A national approach to innovation systems focuses on a facilitatory regulatory environment, education and training system, financial support mechanisms, amongst others. Finally, the key to an innovation systems approach in the economics literature is a focus on firms. It argues that these actors (not always private-sector owned) are the loci of innovation and should be supported.

Thus, the innovation systems approach is relevant for those thinking about invigorating the micro-digester sector in South Africa because:

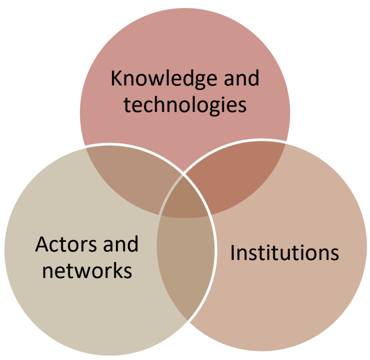
1. It focuses on breathing new life into the country's economic activities. This is relevant here as the micro-digester sector in South Africa could be argued to be at the point of stagnation.
2. It recognises all the actors involved in the micro-digester space and promotes a move away from the reliance on development partners or government-funded schemes[1]
3. It focuses on long-term viability and economic sustainability and how this links to social and environmental sustainability. This has increased in recent years with the rise of 'transformative innovation policy' thinking (Schot and Steinmueller, 2018).[2]

A sectoral innovation systems perspective

This report does not focus on national systems of innovation but rather a sectoral innovation systems lens (c.f. Malerba, 2005). Malerba (2005: 65-66) describes a sectoral innovation system thus:

> "Sectoral systems of innovation have a knowledge base, technologies, inputs and a (potential or existing) demand. They are composed of a set of agents carrying out market and non-market interactions for the creation, development and diffusion of new sectoral products. These agents are individuals and organisations at various levels of aggregation, with specific learning processes, competencies, organisational structure, beliefs, goals and behaviours. They interact through processes of communication, exchange, cooperation, competition and command. Institutions shape their interaction. A sectoral system

Figure 3: Elements of a sectoral innovation system



[1] This is not to say that no government funding or incentive schemes should be promoted. In fact, there is increasing recognition of the need for 'mission oriented' or 'challenge oriented' innovation (c.f. Mazzucato, 2018) which relies on targeted government funding and support.

[2] The sustainability focus of national innovation systems is of some debate with a number arguing there has always been a focus on social and environmental issues (Fagerberg, 2018)

undergoes processes of change and transformation through the coevolution of its various elements."

As such, a sectoral innovation system is made up of three main elements:

- **Knowledge and technology**: A sector is shaped by the dominant technologies, knowledge and skills base and inputs available to the sector. The degree of innovation in technologies and the strength of the knowledge base, and the availability of inputs will determine whether and how the sector grows or contracts in size.
- **Actors and networks:** private firms are central to innovation systems but interact with a range of actors, including public sector organisations (e.g. universities, research centres, government departments) and third sector (e.g. non-governmental organisations or community groups) as individuals. Sectoral innovation occurs across a range of geographical boundaries as many sectors rely on inputs from sources not always local to them, including product supply firms or investors in other parts of the country and/or abroad. The quantity and quality of interaction – the level of networking taking place – determines the intensity and type of innovation that takes place. This networking may be formal or informal, bilateral and multi-lateral in nature and can involve the sharing of knowledge and skills and formal technology transfer or investment.
- **Institutions:** Actors are to the 'rules of the game' both formal (e.g. legislation and policy) and informal (e.g. attitudes and norms) as well as dominant narratives that determine how actors and networks operate and interact as well as the types and ways in which knowledge and technologies are produced, distributed and taken up.

Innovation in the South African micro-digester sector

Before we focus in-depth on the sectoral innovation system, it is pertinent to consider the type and scale of innovation taking place in the South African micro-digester sector. As we have outlined above, innovation is the introduction of something new into an environment. The main forms of innovation can be classified as follows:

- Product innovation: the introduction of a new or improved good or service.
- Process innovation: the introduction of a new or improved way of producing or delivering a good or service
- Business model or marketing innovation: introducing a new way to create value for an organisation and/or consumers.
- Organisational innovation: the introduction of a new way of working or operating to increase performance and/or efficiency

We have also mentioned above the concept of social innovation or the use of new to context collective action to meet social goals. There are overlaps here with organisational innovation and, in the context of this study, we will use the term organisational innovation. This is because we can see all efforts relating to biogas use are fundamentally focused on meeting various social goals relating to waste management, climate change mitigation and food security.

Here we outline the evidence gathered from our literature review and discussions with academics working in South Africa on different types of innovation in the micro-digester sector.

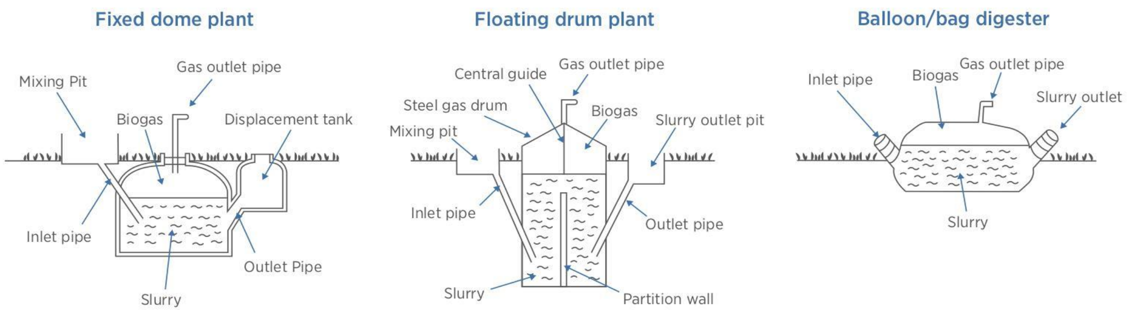
Product innovation

There is little evidence of product innovation in the South African market; instead, it is dominated by 'proven technologies' (Resmani, 2021). Six main designs dominate the market (Mutungwazi et al. (, 2018): fixed dome; floating drum; Biobag; Puxin; Aget;[3] Plastic rato. The three most popular designs are the fixed dome, floating drum and ballon or biobag (Figure 2).

Micro-digesters in South Africa tend to range from 1m³ to 20m³ (see Table 2), although some categorise them up to 100m³. These tend to require manual feeding with feedstock (e.g. cow dung and/or food waste), rarely include a gas storage chamber (as illustrated by pictures in Figure 2) and therefore provide gas directly to a stove top burner and used for cooking.

Reviewing the literature, we find several technical barriers (Table 1) affecting the design of biodigesters and which has implications for their uptake and use. Our survey of Sanedi supported micro-digesters found 47% (21 out of a total of 44 micro-digesters surveyed) were non-functional. Many of the reasons for their non-functionality relate to the availability of feedstock, cracks and disrepair (due to poor construction) and/or poor operation (notably clogging of the digester and/or insufficient gas production due to the wrong chemical balance). This fits with the literature, which has identified a range of technical barriers in the designs of the main micro-digester (see Table 1).

Figure 2: three main micro-biogas digester types



Source: Reproduced from IRENA (2017, p.10)

Table 1: Technical barriers to current dominant micro-digester designs

TECHNICAL FACTOR		FINDINGS
FEEDSTOCK AVAILABILITY	Sufficient feedstock must be available to produce biogas.	Certain market segments may not be able to maintain the digester throughout the year. Seasonal feedstocks may reduce biogas production rates.
WATER AVAILABILITY	An adequate supply of water is required for the anaerobic digestion process.	Potential customers would need to consider the viability of installing a digester if the water supply is not secure. Consider the cost of water when assessing economic feasibility.
CONSTRUCTION AND INSTALLATION	Skilled staff are required to construct or install prefabricated digesters.	Construction issues are frequent for built digesters. Training programmes have not always been successful. -Material for construction is locally available.
	Availability of materials.	Prefabrication leads to standardisation and quality assurance.
OPERATION AND MAINTENANCE	Technical failure due to poor construction/ manufacturing. Lack of attention to maintenance. Lagging service management.	Digester longevity needs to be considered. Digesters are not always maintained. Poor performance due to maintenance issues negatively impacts perceptions.

[3] Designs by African Green Energy Technologies, a Cape Town based company

There are, however, opportunities for product innovation in this sector. Rasmeni (2021) mentions two: the introduction of real-time data capture using sensors in the digester to enable more effective monitoring of the system and; the introduction of disinfection systems into the design of the slurry chamber to sanitise the digestate and gas produced. A review of the literature (c.f. Jain, 2019; Lemonde, 2020) found additional product innovations that may be relevant for South Africa to include:

1. The addition of a macerator to reduce the size of food waste being entered to increase the efficiency of digestion[4]
2. Direct piping of feedstock into the mixing pit/ inlet pipe from the source (e.g. toilets, animal slurry pits)
3. Introduction of gas storage tanks to reduce waste of excess gas, especially in fixed and floating dome designs[5]
4. Full automation of the product so that the system requires no daily physical monitoring or routine maintenance (e.g. gas-letting)
5. Direct piping of gas to heat greenhouses
6. Small plug-and-play or mobile systems for urban environments[6]

Process innovation

Rasmeni (2021) highlights that while the design of a digester may change, the anaerobic digestion process does not. However, that does not mean that process innovation cannot take place. The inclusion of additives, mixing technology, insulation and perfecting the quality and mix of feedstock have all been studied as possible process innovations (Tabatabaei et al, 2020a; Tabatabaei et al, 2020b; Singh et al, 2020). We have found little literature that provides evidence of any of these innovations taking place in South Africa.[7]

Business model innovation

As noted above, business model innovation is focused on adding value for an organisation or user. In South Africa, there is very little value creation in the micro-digester sector. Business model innovation tends to occur once product and process innovation has already taken place and accepted technologies provided by multiple actors are the status quo (Massa and Tucci, 2013). The creation of value involves organisations becoming involved in new activities (e.g. selling new, allied equipment), creating new ways to generate revenue (e.g. new pricing models) or creating new linkages with other actors (e.g. new relationships with customers or suppliers) (Massa and Tucci, 2013). Rasmeni (2021) notes that there are opportunities to encourage value creation for the consumer by using the fertiliser created from the digestate. They state that biogas digesters installed by AGAMA Biogas (SA) Ltd across South Africa had produced 165,000 litres of liquid fertiliser. A 2020 UJ-PEETS report of an online action dialogue meeting also reports one case study at Speir Wine Estate that had been producing fertiliser. That said, the survey of Sanedi supported micro-digesters conducted as part of this study by UJ-PEETS found that of the 24 functioning micro-digesters out of the 44 studied, only 11 (46%) were using the slurry produced for gardening or farming. As such, when you add up those not using the fertiliser and those not functioning, three quarters (75%) of the whole sample were not using the fertiliser opportunity provided through a micro-digester. During the stakeholder mapping workshop held for

[4] It should be noted that some of the Sanedi projects are investigating this given problems schools have had in ensuring sufficient gas supply due to blockages caused from food waste being added of the wrong size.

[5] Balloon/ bio bag digesters allow of a modular system already where more bags are added as increased capacity is needed.

[6] A action dialogue meeting held in 2020 by UJ-PEETS identified plug and play solutions as being an important area for further investigation

[7] Mutungwazi et al (2018) note that many of these process innovations can be found at the industrial or agricultural level from 25kW in South Africa

this study, one participant managing 55+ micro-digester sites noted that efforts were being made to change the policy landscape (see below), which would enable more business model innovation in this area.

Rasmeni (2021) also note the possibility to use the gas produced for lighting and electricity. There are few examples of this taking place that we have found in our literature review. Africa green energy technologies (AGET), a private company selling various sizes of the biodigester, have a case study ($20m^3$) on their website that shows biogas being used for lighting. It is not clear if this was, in fact, installed. Rasmeni (2021) also note the importance of building up the waste management narrative. This issue was also raised in the online action dialogue held by UJ-PEETS in 2020, given the change in some provincial government's rules on organic waste to landfill (see discussion of institutions below). We find little evidence in the literature we have read or meetings we have held that companies or organisations working in the space are actively promoting waste management focused business models. We have a couple of examples of Sanedi-supported micro-digesters fed using waste collected and/or purchased from other organisations/ individuals. We discuss this under organisational innovation below.

We had found examples of other business model innovations in other countries – often with slightly larger micro-digester systems ($20\text{-}50m^3$) – which could be considered in South Africa. These include:

1. Pay-as-you-go or payment in instalment schemes for those buying a micro-digester to make them more affordable to the consumer (Jefferys, 2019)
2. Sales of gas produced being bagged or bottled for sale to the surrounding community as a clean cooking fuel (Mphande, 2020; Twinomunuji et al., 2020)
3. Charging of batteries, lights and mobile phones using biogas generator (Cherry et al., 2014)
4. Gas or digestate being used to fuel vehicles[8]

Organisational innovation

The sales of gas produced to local communities for their cooking needs, the charging of appliances using a biogas generator, or the collection of organic waste from the community all require not just business model innovation but also organisational innovation. It requires a different way of organising, a different combination of actors. As noted above, we have at least one example from the Sanedi-supported micro-digesters where organisational innovation has taken place. In this instance, a community-based organisation was set up to run a digester at a school. The community group organised to collect feedstock from the community (paying for the feedstock provided) and was paid for the provision of the gas to the school. The 2020 action dialogue event again highlighted the potential of community-scale utility models. Such examples have been found successful elsewhere, such as in Malawi at Tsangano market run by Green Impact Technologies (GIT) in a public-private partnership with Malawi University of Science and Technology and funding from Malawi's National Commission for Science and Technology (Mphande, 2020). GIT takes waste from the market and produces biogas that is bagged and sold to local restaurants and eateries, amongst others in and around the market. Another example is Khainza Energy Gas in Uganda which buys organic waste from smallholder farms and local households and then sells the resulting gas to local consumers (Mbaka, 2020).

The decision to develop any of these innovations by any company or organisation will need to be based on a review of the market demand as well as the availability of skills and capabilities, spare parts and ability to repair and maintain, the cost as well as the social acceptability of any of the innovations.

[8] AGET's website has a case study of the gas from a $20m^3$ micro-digester being used to power some farm equipment.

The main elements of the micro-digester sectoral innovation system

Against this background of the status of innovative activity in South Africa, we can now look at the elements that support or block these different forms of innovation in the South African micro-digester sector. As noted above, there are three main elements of this sectoral innovation system: institutions, actors/ networks and knowledge/ technologies. We will address each of these in turn.

Knowledge and technologies

We have already discussed the status of the product and process innovation – the technologies – that are available. What was not discussed above was the utility of these different technologies. The table in Annex 3 provides a general overview of the main available micro-digester products that are available in South Africa. The table includes the main challenges affecting each product's installation, operation and maintenance. The table is reproduced here (Table 2) for ease of reference.

From this table, we can see that the price of the products varies enormously (we return to price issues shortly), as does their lifespan. These results are mirrored in Rasmeni (2021). In particular, those built with locally available resources are often cheaper but are prone to maintenance issues and frequently crack and/ or become non-functional.

As part of this project, we also conducted a techno-economic analysis of two of the main digester types: a fixed dome brick and mortar 12m^3 digester and a 15m^3 balloon biobag. Due to the difficulty of getting accurate data across multiple data points, we utilised data for the highest-performing digesters with the best quality data. The fixed dome brick and mortar micro-digester was located at a homestead in Limpopo province, while the biobag was located in a school in Gauteng province. The results found that assuming the digesters can be operated at 80% of their design output (gas), the levelized cost of electricity (LCOE) for the fixed dome digester is USD 72 per MWh, while the levelized cost of cooking (LCOC) is USD 77 per year respectively. The analogous figures for the biobag digester are USD 127 per MWh and USD 136 per year, respectively. The difference between the two product types being the consequence of the higher capital cost per m^3 of digester volume; based on the capital expenditure costs we received. These results are similar to the literature values (LCOE between USD 50 to USD 200 per MWh and LCOC at USD 50 per year) and lower than the costs of alternative energy sources such as electricity and biomass.

However, the data from the fieldwork indicates that even these digesters are operating at only 20% of their design capacity, with the result that the LCOE and LCOC values are between 1.5 (fixed dome) and four times (biobag) the cost of either grid-based electricity or bottled LPG. Similarly, at this gas output, both projects have a negative Net Present Value, indicating that a private investor, unable to draw on a government grant, would not earn a return on investment should she decide to invest in a similar facility.

While there are problems with the available technology, the key to improving that technology is the knowledge base that supports innovation. This relates to the level of research ongoing at higher education institutions and research centres relating to the design, production and use of micro-digesters. It also relates to the number of skilled technicians working in companies that design, manufacture, install and/or repair the technologies. Through Rasmeni (2021) and across the literature review, we can identify seven universities and research centres conducting research and training on micro-digesters in South Africa. These research micro-digester design, techno-economic analysis, as well as the barriers and opportunities to their uptake.

Table 1. Summary of micro-scale digesters in South Africa

	Brick and mortar fixed dome digester	Floating drum digester	Balloon/bag Digester	Underground digester 10m^3 (AGET)	Portable digester 2.5m^3 (AGET)	Fixed dome digester (EZ-Digester)	The Little green monster	Moulded fixed dome (AGAMA)	In-situ cast concrete digester (Puxin patent)
Size (volume)	4-20m^3	1.2-15 m^3	15m^3	10m^3	2.5m^3	1.5m^3	2.5m^3	6m^3	10m^3
Gas output/ day	Varies	Varies	5m^3	8m^3	2m^3	Not available	2m^3	2m^3	3-5m^3
Feedstock	Varies Manure, organic waste	Varies Manure, organic waste	200kg Manure, organic waste	120kg Manure, organic waste,	5-8kg Organic waste	25kg Organic waste	Organic waste	40kg Manure, organic waste	80-100kg Manure, organic waste,
Cost	Up to R60000	Up to R60000	Up to R60000	Not provided	Not provided	R12000	Not provided	Not provided	R60000
Main Materials	Brick and mortar	Steel	PVC Insulation required to maintain temperature.	Concrete (digester) Plastic (biogas bag)	Plastic.	Plastic, moulded. Portable.	Polyethylene plastic, moulded.	Plastic	Steel, concrete, fibre glass
Expected life	3 years	8 years	15 years	Not provided	Not provided	10 years	20 years	Not provided	30 years
Installation and operation	Excavation required. Gas at variable pressure – inefficient for equipment.	Excavation required. Simple operation. Monitor for fibrous materials.	Easy to install. Excavation required. Constant monitoring of slurry level. Slurry dilution when rains.	Excavation required. Portable biogas bag for indoor use.	Mobile Includes integrated photovoltaic module for gas pump.	Prefabricated. Above ground. No temperature controls. Manual agitation required.	Prefabricated. Excavation required.	Prefabricated. Above ground.	Excavation required.
Maintenance	Cracks and gas leaks are common. Ground may also destabilise.	Corrosion of steel parts and sliding mechanism.	Slope distortion needs to be monitored. Fails due to lack of agitation.	Not provided	Not provided	Prone to clogging, ongoing maintenance.	Maintenance to remove soli sludge.	Maintenance for cleaning.	Easy to clean.

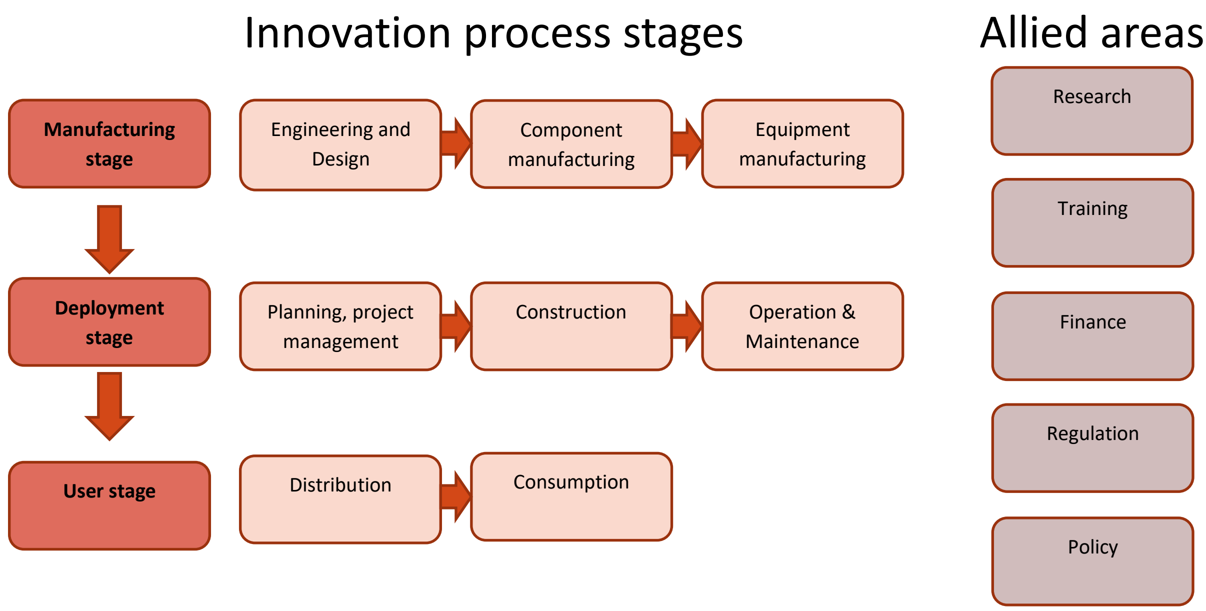
Source: DIFD 2011; Mutungwazi 2018; Rajendran 2012

There are competing data on jobs in the biodigester field, with figures from 1,700 jobs (Sagen, 2016) to 270 jobs (GIZ-Altgen, 2016). Either way, there is widespread recognition that there are insufficient training schemes in the micro-digester space (Rasmeni, 2021). A quick internet search finds evidence of once-off training offered by a variety of private-sector firms, research and consulting firms over the last few years in South Africa on how to operate and maintain a biogas digester. The GIZ-Altgen report (2016: vi) concludes: that there is a need for "standardised qualification for biogas plant design, operation and maintenance". Rasmeni (2021) reiterate this recommendation. That said, our internet search did find a new Biogas System Optimisation Training being offered in 2020 by South Africa's National Cleaner Production Centre, which is certified by the United Nations Industrial Development Organisation (UNIDO).

Actors and networks

Innovation systems are a function of the actors who are involved in them and how they interact. These actors can be broken down into a range of different groupings related to their roles in the innovation process. Figure 3 identifies the key actors' groupings and their main activities across the different phases of the innovation process. We then list the key actors visible in the South African micro-digester sector in each of these actor groupings.

Figure 3: The innovation process and allied areas in South Africa



Source: author

Manufacturing stage

There are several established manufacturers of micro-digesters in South Africa. The three most cited and well-known are:

- Biogas SA – licence to build and assemble the Chinese patented Puxin digester and build fixed dome and biobag digesters of varying sizes. They also sell output equipment, including biogas stoves, rice cookers, lights, generators and hot water heaters. Their website also advertises that they well pipe and fittings for biodigesters.

- AGET – manufacture a fixed dome model as well as a biobag model. They also sell output equipment, including biogas stoves, rice cookers, lights, pumps, room heaters and generators.
- Agama Biogas – manufacture and build a moulded fixed dome digester of various sizes. Their website advertises that they also sell biogas water heaters and stoves as well as biogas fittings.

Most of the components required for assembly (pipes, taps, etc.) can be bought from South African manufacturers, which have established plastics manufacturers and metal fabrication firms certified to international standards. This is not the case with much of the output equipment (stoves, water heaters etc.), which we understand are mostly Chinese in origin.

Deployment stage

The three companies above are also the leading private sector companies involved in the project management of micro-digester projects and their construction. That said, the vast majority of micro-digesters in South Africa are the result of a development partner and government-funded projects[9] which a range of partners has introduced; notably through Sanedi's Working for Energy programme, which has involved Mpfuneko Community NPC, Vatsekeme Community Group, University of Venda, Khanyisa Projects, EnergyWeb, University of Kwa Zulu Natal and Gauteng Department of Infrastructure Development.

Operation and maintenance activities in Sanedi-supported micro-digesters has been conducted by the universities and community-based organisations listed above. The three leading private sector companies also provide repair/ maintenance services.

User stage

We have the same three private sector companies, Sanedi and its partners, as the key distribution actors in the user stage. In terms of consumers, the size of the micro-digesters being offered means that the consumer base is predominately focused on rural homesteads with one or two cows or public facilities such as schools and early childhood development centres where there are feeding programmes. That said, Mutungwazi et al. (2018) note that Agama Biogas has installed digesters for facilities in the tourism sector and larger farms and estates.

In fact, our review of market potential(Annex 3 and summarised in Box 1) identified three target markets, broadly grouped into households, communal spaces and public facilities, and hospitality establishments (DIFD 2011; IRENA 2017; Thiriet 2020). Households can be further segmented into rural and urban households, electrified and without electricity access. Community facilities include schools, nursing and care homes, and other community-orientated centres. The hospitality segment includes wine, game and bush farms, and restaurants and public and private canteens.

[9] We state this based on the idea that of the 350 micro-digesters apparently installed in South Africa over 100 have been installed under the Sanedi Working for Energy programme. At the same time however, Mutungwazi et al (2018) states that Agama Biogas has installed 320 micro-digesters. There is therefore some further interrogation of the installation figures required.

Box 1: A review of potential markets for the South African micro-digester sector

Main findings from a market review

Annex 3 provides an overview and analysis of the market potential for micro-scale anaerobic biogas digesters in South Africa. The market potential for a product or technology is a function of a target market's size and the product's estimated penetration rate into that market. This report draws on international, regional and national literature and national economic and socio-economic data to estimate the size of the identified target market segments.

Theoretically, households represent the most significant potential target market for micro-scale digesters in terms of volume. The most recent figures estimated some 16.7 million households in South Africa. Gauteng Province has the largest number of households, while 58% of households are concentrated in the largest three provinces: Gauteng, KwaZulu-Natal, and Western Cape. This market can be further segmented between rural and urban households. Rural households are typically larger, where 20.6% have six or more members, and 24.3% have 4-5 members. Approximately 79% of rural households also own livestock that produces manure. However, most of the country's population (over 90%) is concentrated in urban areas. While the initial focus of many pilot projects in South Africa (and, indeed, internationally) has been on rural households, urban households all represent potential customers of micro-digesters. For market segmentation, a further differentiation between city and peri-urban households may be helpful.

Other important market segments include community facilities including schools, nursing and care homes, and other community-orientated centres – there are over 30,000 schools in South Africa alone. The third key market segment for micro-digesters is the hospitality segment including wine, game and bush-farms, as well as restaurants and public and private canteens. This last market segment is numbered to include at least 20,000 possible establishments.

Considering the very low penetration rate in South Africa, in conjunction with our estimated penetration rates internationally, scenarios for market penetration at 0.05%, 0.1%, 0.25%, 1%, and 10% were considered for each market segment. In the most optimistic scenario the market size is: 1.6 million (mostly peri/urban) households, 3,000 community and 2,000 hospitality facilities.

The report concludes that approaches moving forward should take a segmented approach, targeting interventions for different markets. This includes choosing the right technology mix as well as targeted interventions to address the individual demand and supply factors for each of these segments.

The ability of each of these potential markets to be penetrated will depend on the facilitatory nature of the enabling environment – of the functional nature of the different elements of the sectoral innovation system (knowledge/ technologies; combinations of actors/ networks and; institutions).

Allied areas of the innovation process

Innovation systems thinking requires the consideration of actors who influence the different stages of the innovation process. These can be broken down into actors involved in research, training, finance, regulation and policy. The key actors in each of these areas that the study has identified are outlined in Table 3. It should be noted that many actors actually have multiple functions and therefore are active in more than one allied area. This is the case, for example, with Sanedi, which is a key research actor but also who have funded a significant level of micro-digester projects.

Similarly, many government departments also fit within the finance, training and regulation areas and the policy area. We have focused predominately on national actors in each area, but there are also many international actors (the most influential of which we have included in the table) but are also influential in the sectoral innovation system. These include international researchers, UN organisations and international development partners, as well as industry organisations.

Table 3: Key actors in allied areas to the innovation process

Research	Training	Finance	Regulation	Policy
South African National Energy Development Institute (SANEDI) University of Johannesburg University of Venda Stellenbosch University Cape Peninsula University of Technology University of Fort Hare University of South Africa Council for Science Innovation and Research	South African Renewable Energy Technology Centre Biogas SA AGAMA Biogas AGET EnergyWeb Khanyisa Projects	German Cooperation (GIZ) Development Bank of Southern Africa (DBSA) United National Industrial Development Organisation (UNIDO)	National Energy Regulator of South Africa (NERSA) Municipal Governments Licensing and permitting authorities	Department of Energy (DoE) Department of Science and Innovation (DSI) Department of Environment, Forestry and Fisheries (DEFF) Department of Agriculture, Land Reform and Rural Development Southern African Biogas Industry Association (SABIA) World Biogas Association International Renewable Energy Agency

Source: author

Networks and linkages

This is perhaps the most important element of any innovation system. How actors across the innovation process stages and the allied areas interact, support or challenge each other will determine the success or otherwise of innovation efforts. It determines the degree to which technologies are promoted and new knowledge is built, and the degree to which institutional rules and norms become dominant.

Our review of the literature has identified very few strong linkages between actors (see Figure 4). We find the strongest linkages are between the research community (universities) and the communities they work with to pilot micro-digester technologies. We also find strong linkages between development partners such as GIZ and UNIDO with government departments, especially funding and support for micro-digester projects and training. This fits within a broader set of relations between development partners and government departments relating to promoting renewable energy use more broadly. There appears to be growing engagement across government departments and national, provincial, municipal governments and community leaders in the area of policy coherence. This is particularly notably around support for renewable energy (very broadly) and the need to tackle youth unemployment. However, there are significantly weak linkages between the private sector and researchers to innovate new designs and ways of working. There are also few linkages between the business and finance communities which has implications for investment in this sector. Similarly, there is a weak linkage between the business sector and the end-user, predominately because there is no real demand for this technology. Finally, the lack of skills and trained technicians suggest a lack of linkage between business and training institutes.

Figure 4: Types and strength of linkages visible in the sector

STRONG	MEDIUM	WEAK
Research – Community (piloting)	Government – Government (policy coherence – RE narrative)	Business – Research (innovation)
Development partner – Government (RE support)	National – Provincial – Local (policy coherence – youth employment)	Finance – Business (investment)
		Business – end user (demand)
		Business – Training institutes

Institutions

Several documents have been developed for this sector review (e.g. Rasmeni and Kajau, 2021, Annexes 3, 4 and 5) that outline the status of the institutions influencing the sector. In these allied documents, the institutional analysis is conducted predominately using a PESTLE-type approach. This approach considers the influences of politics, economics, and social, technological, legal and environmental factors. We have discussed the technological factors above under 'knowledge and technologies'. We will now synthesis the main areas of discussion in each of these other factors here below. We do not go into these in any depth because they have been so well articulated elsewhere. Some of these factors are enabling, while others have been disabling the micro-digester innovation system.

Table 4: PESTLE factors impacting the South African micro-digester sector in 2021

POLITICAL FACTORS	Three-tier government system with policies that rarely mention biogas
	Existence of lobby group (SABIA) but which, until recently, was focused on larger scale digesters
	Focus on clean energy access (for cooking) and rural areas
ECONOMIC FACTORS	The cost of micro-digesters is high relative to the cost of electricity and other fuels
	Subsidies have been used through promotional programmes; no real market for micro-digesters
	Lack of availability of finance, rising inflation and high interest and poor exchange rates
	Potential opportunity for market growth from the existence of some economic incentives, e.g. carbon tax; payment for ecosystem services
SOCIAL FACTORS	Traditional attitudes to cattle ownership, waste management, gender roles
	Population levels in urban, peri-urban and rural areas
LEGAL FACTORS	Few dedicated regulations for micro-digesters
	Legal requirements in some provinces on organic waste to landfill with targets
ENVIRONMENTAL FACTORS	Availability of water
	Odour and pollution from leaking micro-digesters

Source: Rasmeni, 2021; Annex 3; Annex 4 and Annex 5

A note on policy

Table 4 highlights a key finding of many reviews, including those in this report (Annex 3, 4 and 5) that there are few dedicated policies for biogas and specifically micro-digesters in South Africa. This is different from other countries where micro-digester penetration is higher (e.g. China, Bangladesh, Cambodia, and Tanzania in Africa). Annex 5 reviews the policies of other countries and finds that those with higher penetration rates also have a facilitatory policy. For example, in China, policy incentives are deemed critical in making it the country with the largest number of installed micro-digesters. The government focused on financial support to the sector through price controls and low-interest rates as it vigorously promoted biogas as a solution to energy access for rural areas. Bangladesh promoted community level digesters as a solution for waste management and set up financial incentives such as micro-lending schemes and investing heavily in technical support. Cambodia focused on policy coherence through a high-level steering committee set up across ministries and capacity building in the policy sphere to enable the sustainability of the national programme over the long term. Tanzania has mirrored Brazil, the US and many European countries in promoting biofuels and had a subsidy scheme in place.

The focus of energy policy in South Africa is predominately on electrification through the grid. However, the REIPPPP has changed the sector's political economy by introducing new actors (see Annex 4). The majority of the new actors are in other renewable energy sectors, notably solar PV. The National Development Plan 2030 specifically single out biofuels as a possible future area for the country to consider. The 2002 White Paper on the Promotion of Renewable Energy and Clean Energy Development also mentions the potential to produce energy from manure and litter. However, all policy focus on bioenergy has been on biofuels at scale and particularly a focus on bioethanol production

A major first step to policy change has been the collaborative development of a set of 'Guideline to Plan and Implement Anaerobic Micro-Digester Projects in South Africa' developed by the National Biogas Platform's Micro-Digester working group with support from USAID and GIZ. Published in February 2019, the document outlines recommendations for project developers, providing advice for clients wishing to procure or build a micro-digester, and acts as a reference document on the status of the field for other stakeholders. Unfortunately, the document could not be found in the public domain at the time of this study (i.e. it is not freely available on any website). The document provides a strong reference point for the sector. It indicates several key areas of policy change that are required ranging from clearer designation on sizing of digesters into micro, small and larger commercial scales to the difficulties of using and selling digestate by-product as fertilizer. Efforts in many of these areas are being made by setting up working groups by the National Biogas Platform, which different stakeholders are leading.

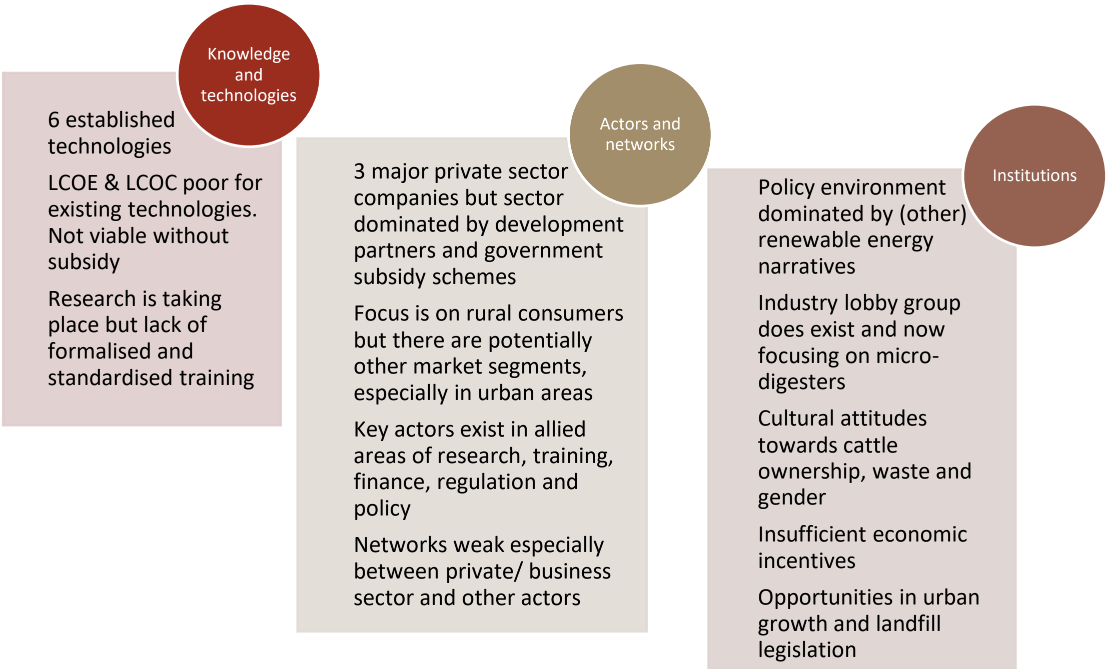
Discussion

The preceding sections have outlined the micro-digester sector using a sectoral innovation system lens. Based on the above, we can build up a picture of the sectoral system and see a series of dominant narratives that influence the sector. We can also identify several gaps or elements that are missing, which should be considered if the micro-digester sector innovation system is to function more effectively.

What does the micro-digester innovation sectoral system look like?

While on the one hand, the sector has several established technologies; they all suffer from design flaws related to everything from their initial cost to the difficulty of maintaining and operating them. There is a significant opportunity for product and process innovation and – and perhaps most importantly – business model and organisational innovation. A key barrier to innovation is the lack of linkages between actors in this field, particularly between the private sector who import, design, manufacture and distribute micro-digesters and the country's researchers. This impacts the level of knowledge within the system. The key to strengthening these linkages is a supportive enabling environment in the form of a strong institutional base. The current institutional base for micro-digesters is lacking due to a lack of policy coherence and dominance of other policy narratives and several economic, social, legal and environmental factors. The current status of the micro-digester sectoral innovation system is diagrammatically outlined in Figure 5.

Figure 5: Status of South Africa's micro-digester sectoral innovation system elements



Source: author

Dominant narratives

Using a sectoral innovation systems lens has identified three dominant narratives influencing the opportunity for and extent of innovation in the sector. These relate to policy, scale and cost.

Dominant policy narrative

As noted above, there is an absence of a specific policy focused on biogas. What policy is available is focused on bioenergy and biofuels, notable bioethanol. More broadly, there is increasing recognition of renewable energy and a move away from fossil fuels in the energy policy narrative, although this is dominated by solar. The focus across the board is grid electrification and/or the use of biofuels for this and/or transport fuel. Policy analysis of other countries shows various policy incentives that can be used to increase uptake of biogas micro-digesters. The Working Group of the National Biogas Platform focusing on micro-digesters has an uphill battle to move the dialogue forward.

Dominant scale related narrative

The policy narrative has focused on biogas anaerobic digestion in industrial-scale plants and has had implications on the level of innovation at the micro-digester model and the lack of focus by the private sector on the market for this size the digester. Those who have focused on micro-digesters (development partners and government agencies such as Sanedi) have focused on rural biogas. However, most of the population live in urban areas, and waste management issues are becoming a significant issue in these environments. One reason for this might be that the National Biogas Platform only set up working groups that were scale focused from 2016 (Goemans, 2017); the micro-digester working group was set up with the merging of the 'small scale' and 'rural' working groups in 2017 (Sanedi, 2017).

Dominant cost-related narrative

The micro-digester sector in South Africa is dominated by subsidy schemes whereby rural households and/or community facilities such as schools receive a micro-digester essentially 'for free'. They are expected to provide the employees to operate and maintain the micro-digester but often do not have to repair (or pay for the repair) of a faulty digester themselves; the subsidising agency undertakes this. The techno-economic analysis conducted for this report highlights that this was the correct model given the low economic efficiency of the technologies being used. However, this approach is not sustainable in the long run, and many digesters fall out of use. The evidence outlined above has suggested that business model and organisational model innovation has the potential to change the cost dynamics and increase the viability of this sector.

Recommendations

This report is based on a wide-ranging literature review and several stakeholder engagements between October 2020 and March 2021. The report has outlined an analysis of the South African micro-digester sectoral innovation system.

- It found that the innovation systems approach is relevant for those thinking about invigorating the micro-digester sector in South Africa because it focuses on breathing new life into the country's economic activities; it recognises all actors involved in the micro-digester space and focuses on long-term viability and economic sustainability and how this links to social and environmental sustainability.
- A sectoral approach recognises that actors within the system are influenced by, and influence, the technology and knowledge in the system. These, in turn, are influenced by the strength of networks. The linkages between each of the elements (their strength and focus) determine the success of a sectoral innovation system. Furthermore, there is a set of (dis)enabling institutional factors that are key to the system's success.
- Specifically, there are established technologies that are being used as micro-digesters in South Africa, but there is limited innovation taking place, especially at the level of business model and organisational innovation. The technologies in use are not financially viable in their current form. The results for levelized cost of energy and levelized cost of cooking were found in our techno-economic analysis to be between 1.5 and 4 times as expensive as grid electricity or bottled LPG gas, even in what is considered high performing micro-digesters.

RECOMMENDATION 1: Move the narrative beyond energy and cooking to bring in the benefits from other value addition available from the use of a micro-digester especially waste management and fertiliser from digestate. This requires agreement by sector stakeholders as to who's role it will be to promote this broader value addition perspective. The obvious candidates for this role are Sanedi and SABIA. **RECOMMENDATION 2:** Encourage business model innovation (e.g. Pay-as-you-go or payment in instalment schemes; sales of gas produced being bagged or bottled for sale to the surrounding community as clean cooking; charging of batteries, lights and mobile phones using biogas generator) and organisational innovation, especially community-based biogas micro-digester schemes.

There are private business actors involved in this sector, and they are supported by an industry lobby group. However, the sector is currently dominated by development partners, and government subsidy schemes focused on rural consumers. This is at the exclusion of potential market segments in urban areas (where the majority of the population live). These require portable and/or modular systems and potentially more community-focused schemes that may be larger in size than those currently being promoted to rural homesteads and community facilities. They also require incentive schemes to encourage more innovation in this sector.

RECOMMENDATION 3: Conduct more research in collaboration with the private sector. This needs to focused on foresight research. More market segment analysis is also needed to understand the potential opportunities (especially in urban environments) and potential models for community-sized systems.

RECOMMENDATION 4: Enhanced demand-pull financial incentive schemes (e.g. innovation competitions) to stimulate private sector interest and public-private partnerships in this sector.

Institutionally, policy support is insufficient due to the limited focus on biogas in the context of bioenergy and biofuels. The focus of policy support has been on industrial scale biogas. The interest in dealing with the growing levels of urban waste (illustrated by one province's move towards eliminating organic landfill waste) provides a window of opportunity for increased policy coherence.

RECOMMENDATION 5: Develop dedicated biogas policies and support legislation by relevant government ministries to enable innovation in the sector. This includes clearer standards and policies to incentivise finance options and training. The guidelines to plan and implement the anaerobic micro digester projects in South Africa need to be accessible and promoted more widely. This will assist industry and the sector more broadly to segment the market and develop strategies to develop the sector.

Proposed next steps

In order to address the gaps in the sector innovation system outlined in the discussion and support the enactment of some or all of the recommendations above, there is a need for further stakeholder engagement – notable the opportunity for the private sector to review and input to the theory of change and the broader efforts to develop the sector.

Theory of change and broader stakeholder engagement

The first step to enacting change in the sector is to ensure that there is a roadmap for the desired change that is wanted. The Theory of Change in Annex 1 is the starting point for this discussion. However, it requires further input from a broad range of stakeholders. It has currently only been seen by a small number of academics working in the sector in South Africa and Sanedi staff. The draft Theory of Change can be used as a living document from which more nuanced discussions with industry actors can be taken – through entities such as Sanedi and SABIA. Specifically, a discussion on the size of digesters, the segments of the market, opportunities for innovation in the sector and the desired change both immediate and longer-term are desired. As noted above, a sector level theory of change provides the opportunity for stakeholders to align their missions and visions and create the basis for win-win solutions.

Sector development plan

It is recommended that the idea to develop a sector development plan is further progressed. This was an output that was discussed at the start of this review process. This report highlights several opportunities to develop the sector, particularly through market segmentation, active support for the sector at policy level and promotion of innovative activity and linkages across the sector. A roadmap for promoting these opportunities is required through the development and promotion of a sector development plan.

A sector development plan is a physical document that outlines the steps required to move an industrial sector from infancy to maturity. Such a document can take a range of formats depending on the stakeholders' requirements, the information, timeline, and resources available. It can range from a short scoping document outlining the key barriers and opportunities available to a sector, including the key stakeholders in this sector. At the other end of the spectrum, a sector development plan can be a very detailed plan of action outlining in minute detail the steps needed and costs of each step to move from point A to point B in terms of product development, deployment and update.

Box 2 provides an overview of the recommended template for the sector development plan document. It is based on the first type of document outlined above: a scoping document that provides a broad roadmap to guide the sector and provides a path towards a detailed implementation plan once the market segments are more effectively understood. The roles of each actor in the system are more clearly defined. This approach recognises that the sector is still very much in its infancy, and there are areas of the sector relating to market demand, training and capabilities, financing and policy support) that need developing.

The template is structured around three sections. The first section would outline the rationale for the plan. The second section would map the key actors and flows between the actors, as well as an analysis of the enabling or constraining nature of the enabling environment and key pillars that make up an innovation ecosystem. We recommend that it focuses on mapping the sectoral innovation system. By innovation, we refer to support the development of new or improved technologies (i.e. biogas digester models) as well as supportive organisational and business model innovation. These latter two types of innovation refer to the need for innovation in policy and practice in the way the sector is managed and how biogas digesters are marketed to increase deployment and use. Such an approach explicitly engages with the need for a systemic approach to promoting this sector if long term change is to be achieved. This section builds on the industry status report developed by UJ-PEETS (Rasmeni, 2021) and its contents, especially its annexes.

The plan finishes with recommendations for sector development based on the situation and opportunities for innovation outlined in earlier sections of the report and in light of an agreed theory of change against which sector development will be promoted and measured. This theory of change is based on the objectives of the Sanedi Working for Energy programme (and its subsequent broader programme on Renewable Energy under which the Working for Energy programme now falls in the 2020-2025 Strategic Plan). Specifically, the objectives relating to job creation, training and other consumer benefits, including improved access to cleaner and cheaper energy and solutions for waste management.

Box 2: Possible Sector Development Plan Template

1. Background

[Outline of the plan's rationale and fit with broader arguments relating to climate change, energy and environment, waste management as well as poverty alleviation, youth/ female employment and industrialisation.]

2. Industry status

History of biogas micro digesters in South Africa

[The story of micro-digesters from first introduction in 1950]

Industry numbers

[An outline the data on current status of micro-digesters in South Africa (age, location etc.) broken down into technology types and investment figures]

Major sector players

[Map of major actors who currently produce, sell, maintain and use micro-digesters and how this has changed over time. Will include profile of actors outside of South Africa who supply those in the country]

SWOT and PESTLE

[A core part of any sector development plan; this outlines the strengths, weaknesses, opportunities and threats to the sector in the context of the political, economic, social, technological, legal and environmental factors influencing the sector.]

3. Innovation system strengthening

Innovation in the sector

[An outline of different forms of innovation that are present in the system and which are not present but might be desirable. This includes formal and informal innovation as well as technological, social, organisational and business model innovation]

Innovation system status

[A discussion (and diagrammatical depiction) of the sectoral innovation system, building on material in Section 2 above including the barriers and opportunities for innovation]

Recommendations for action

Theory of change

[The inclusion of the final agreed theory of change for the sector]

Recommended next steps

[A series of proposed action points – as agreed on with sector stakeholders – that will provide a guide for sector development over the next five years.]

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Annexes

The following annexes are attached to this document. These are stand-alone reports that were commissioned to provide input to the overarching policy and innovation system report. As a result of each of these being a stand-alone report, there is some overlap in their content.

Annex	Output	Description
1	Theory of change	A theory of change table with the rationale for sector development based on a literature review and feedback received during a theory of change workshop
2	Techno-economic analysis	An economic feasibility of the technology, including an analysis to determine the technical and financial feasibility of two main micro-digester types.
3	Political-economy analysis	Focusing on the actors, institutions, structures and resulting narratives that dominate the sector and their impact on the sector.
4	Market analysis	Review of current market barriers and opportunities
5	Policy review	A review of policies used to promote biogas digesters in several key countries that have had relative success in promoting biogas digesters in Asia, Europe, Latin America and Africa. It also outlines the key policy documents that relate to biogas digester promotion and use in South Africa.

Annex 1: Theory of Change

Theory of Change and Impact Pathway						
Hypothesis	**Inputs**	**Activities**	**Outputs**		**Outcomes**	**Impact**
What it the problem we are trying to solve?	**What resources are needed to bring about change?**	**What steps are needed to bring about change?**	**Measurable effect of our work?**		**What are the wider benefits of our work?**	**What is the long-term change you see as your goal?**
There are significant variations in energy access and a high level of energy poverty. [1] South Africa suffers from significant food waste, sanitation and water access issues. There is increasing need to recognise the interconnectedness of these issues. [2] The biogas micro-digester sector is not a large part of the renewable energy industrial sector. As a result, the sector lacks skills and capabilities. [3] There is a low level of awareness and demand for digesters relative to other forms of renewable energy, cooking fuel, biowaste options and/or fertilizer. [4]	Funding by public, private and community players Skilled and trained technicians and micro-digester operators Knowledge and data on the most appropriate technologies, business models, mechanisms to increase availability of feedstock and use of resulting gas and slurry Facilitatory policy and regulatory support	Applied research on biodigester technology, need and demand, barriers and opportunities to demand and access, market and business, skills and capabilities etc. Deployment of most effective biogas micro digester technologies (designed, manufactured, maintained by local firms) Training and capacity building efforts in relevant design, build, operation, maintenance of biogas micro digester technologies and use of fuel and slurry Monitoring, evaluation and learning activities to inform policy development Policy and advocacy work to promote and enhance enabling environment for the industry Funding provision is enhanced through multiple sources	Economic Dimensions	% increase in employment (baseline: 1,700 employees in the sector, 2016) + increase in income by manufacturers, builders, operators and repair staff of micro-digesters (no baseline) + increase in savings by users of gas and slurry from micro-digesters (no baseline) Rise in number of industry players/ expansion of market (baseline is # of members of SABIA operating in micro-digester sector in 2021) + increase in financial support options available to those purchasing a micro-digester and those working in micro-digester sector	+ increase in total number of micro-digesters utilised in South Africa and + increase in number of functioning digesters (baseline is 700 and 1/3 functioning) Evidence of business expansion by manufacturers, installers, repairers and/or users of micro-digesters (no baseline) Evidence of new partnerships created and maintained between private, public and third sector (no baseline) Evidence of positive change in policy environment e.g. references to micro-digesters in policy documents and debates (no baseline) + increase in awareness of micro-digesters and their value across South Africa (by renewable energy sector players as well as in the community)	Reduced energy poverty (baseline available for certain areas and across different years) Reductions in greenhouse gas emissions created by organic waste in South Africa (baseline 4.3% from Oelofse, 2019) Zero organic waste to landfill targets met by provinces that have introduced these Increased awareness of water-energy-food nexus Increased share of renewable energy sector filled by micro-digester market Reduction in youth unemployment especially in rural areas Increase in female participation in the renewable energy sector as business owners, employees or technicians
			Social Dimensions	Increased number of community micro-digester schemes (no baseline) Increase in number of training and capacity building schemes for building, maintaining and operating a micro-digester (no baseline) Increase in women and youth as micro-digester business owners/ employees/ technicians (no baseline)		
			Environmental Dimensions	Increased access to cleaner cooking fuels (baseline available in certain areas and different years) Reduction in organic waste going to landfill in communities were micro-digesters are used (no baseline) Reduction in household emissions in households using micro-digesters (baseline for 2020 in certain parts of Limpopo only) Increased use of organic fertilizer in communities where micro-digesters present (no baseline) Increased environmental awareness in communities where micro-digesters present (no baseline)		
			Technology Dimensions	+ increase in number of new or improved micro-digester technologies are on the market (baseline is 6 c.f. Mutungwazi, 2018) + increase in number of technologies designed and manufactured in South Africa (baseline is 3 i.e. Aget; Agama and Little Green Monster c.f. Mutungwazi, 2018. Excludes bricks and mortar version) Increase in training programmes (any level of education) on design, build, operate and maintain micro-digesters (no baseline)		

Annex 2: Techno-economic analysis

Executive Summary

Over the last five years, this study has sought to complete a techno-economic evaluation of the South African National Energy Institute (SANEDI) micro digester programme. Standard techniques of levelized cost of energy (LCOE), levelized cost of cooking (LCOC), and net present value (NPV) have been used to determine the economic feasibility of the programme and its individual sites.

Unfortunately, the study has been handicapped by the lack of available input data, especially values for all aspects of the costs, the output of gas, the reliability of the digester and the accrued benefits to the users. This absence of reliable data has made the study more difficult, increased its reliance on literature values for the key performance parameters, and created some uncertainty in terms of the results. To partly resolve the problem, the study has focussed on the two high-performing units, the first being the fixed dome digester at Chavani and the second being the biobag located in Sharpeville. It is noted that out of the 35 digesters covered by the field work across two provinces (Gauteng and Limpopo), only 22 were partly functional, and many were not able to provide reliable information on costs and benefits.

Assuming that the digesters can be operated at 80% of their design output (gas), it is calculated that the LCOE and LCOC values for Chavani are USD 72 per MWh and USD 77 per year, respectively. The analogous figures for Sharpeville are USD 127 per MWh and USD 136 per year, respectively, the difference being the consequence of the higher capital cost per m^3 of digester volume. These results are similar to the literature values (LCOE between USD 50 to USD 200 per MWh and LCOC at USD 50 per year) and lower than the costs of alternative energy sources such as electricity and biomass.

However, the data from the fieldwork indicates that even these digesters are operating at only 20% of their design capacity, with the result that the LCOE and LCOC values are between 1.5 (Chavani) and four times (Sharpeville) the cost of either grid-based electricity or bottled LPG. Similarly, at this gas output, both projects have a negative NPV, indicating that a private investor, unable to draw on a government grant, would not earn a return on investment should she decide to invest in a similar facility.

The challenge from the SANEDI programme, if it is to become more sustainable, is to ensure that the digesters are fully functional, the energy demand is matched by the available feedstock, and that the digester is sized accordingly. Any misalignment of these design values will negatively affect the economics. Furthermore, this study has shown that the fixed dome brick and mortar design, as used at Chavani, has a 50% lower LCOE relative to the biobag structure in Sharpeville, due mostly to the high capital cost of the latter.

A further challenge is training in the operations and maintenance of biogas digesters (especially given the limits to the technology currently utilised). Anaerobic fermentation is a difficult technology and cannot be left to kitchen staff with limited knowledge of the process and its operational requirements. Without this, it is unlikely that digesters will operate at 80% to 100% capacity and therefore be financially viable against other energy sources for cooking.

Finally, this study has been unable to effectively measure the potential additional impact of the technology in terms of costs saved relating to waste disposal (in the case of schools or similar public facilities) and/or digestate created. Further studies that build these costs into a techno-economic analysis are needed to fully understand the financial viability of this technology and its relative merits for different market segments (public facilities, private homes or farms etc.) in different geographical locations (urban, peri-urban and rural).

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Introduction

The Process Energy and Environmental Technology Station at the University of Johannesburg (UJ-PEETS) is presently collaborating with the South African National Energy Development Institute (SANEDI) to review the impact of SANEDI's activity on the micro digester space over the last five years and to plot an approach for the next five years.

As part of this review, UJ-PEETS has been requested to undertake the following tasks:

- provide a feasibility report identifying gaps and recommendations on creating awareness, education and training on developing the micro digester industry in South Africa
- complete a techno-economic evaluation of the micro digester programme over the last five years
- prepare a sector development plan based on possible further collaboration with SANEDI and covering the needs for capacity development, awareness, education and training, and possible product/process optimisation leading to the development of the micro digester industry in South Africa.

This report covers the results of the techno-economic evaluation of the programme.

Background Literature

Technology

The essence of a micro digester is the anaerobic digestion of the feed (typically animal or vegetable waste) to produce biogas and digestate, as shown in Figure 1. Biogas can be used for heating/cooking, gas lamps, or, at a larger scale, to generate electricity using a gas turbine (Jarrar et al., 2020; Jain et al., 2019).

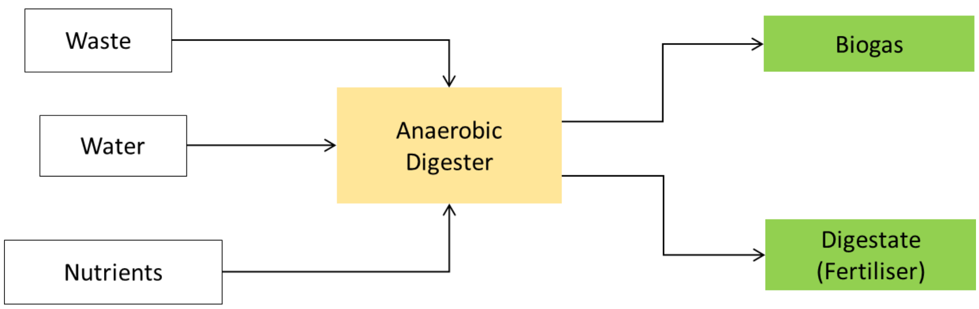


Figure 1. Block diagram of an anaerobic digester

There are several key variables concerning the digester and the feedstock, all of which influence its economic performance. Firstly, there are various designs for the micro digester, including fixed dome, floating cover or drum, and biobag, balloon or tube digesters (Mutungwazi et al., 2018; Cheng et al., 2014; Surendra et al., 2014; Bond and Templeton, 2011). Each type of micro digester is typically made of a different material of construction, with the fixed dome being built using brick and mortar, the floating cover of mixed materials but usually metal and concrete or fibreglass, and the bag digesters from polyethylene or similar plastic (Zheng et al., 2020). Brick and mortar digesters are normally constructed on-site, and fibreglass/plastic units being fabricated off-site but assembled on-site with all the associated equipment. Variations in the material of construction lead to a wide diversity in capital cost; this issue is discussed in more detail in Section 0.

Another important variable is the feedstock. High BOD[10] feedstocks such as animal manure and abattoir waste have higher biogas output per unit mass of feedstock and are ideal feedstocks for micro digesters. (IRENA, 2017). Since capital cost is a direct function of digester capacity (volume), higher energy feedstocks lead to lower operational and capital costs. This issue is discussed in more detail in Section 0.

The third important variable, which also influences the biogas cost, is the anaerobic reactor's size. Micro digesters, the subject of this study and are also referred to as family digesters, are typically 5 to 15 m^3 in volume with a gas output of 0.5 m^3 per m^3 of digester volume (Mutungwazi et al., 2018; Bond and Templeton, 2011). This output is equivalent to 3.2 kWh gas per m^3 per day, which is about 50% of the highest reported values but a reasonable average for the purposes of this study.

An informative comparison of an onsite-constructed digester (OCD), a bag digester (BD) and a composite material digester CMD) is given in Table 2 (Zheng et al., 2020). BD versions tend to be less costly than the OCD equivalent, are quicker to install, and are easier to maintain. Interestingly, the experience on the SANEDI programme is different; the four biogas digesters installed in the Gauteng area were more expensive than the fixed dome brick and mortar structures used in Limpopo. Moreover, the capacity utilisation was lower than the OCD digesters. This issue is discussed in the more detailed field report on the programme.

Table 2. Comparison of various types of digesters according to cost and serviceability

Parameter	OCD	BD	CMD
Cost	Typically, 300 USD to 800 USD	20 USD to 200 USD; significantly less than that the cost of OCD	300 USD to 100 USD; similar to or slightly higher than OCD
Construction cycle	Up to 20 days	Less than 1 day	Typically 1 to 2 days
Service life	More than 10 years with adequate maintenance	Varies significantly depending on materials; generally less than 10 years	More than 25 years; even longer for underground types
Maintenance	Frequent, generally once every two years	Almost none	Almost none
Transportation	Extremely heavy construction materials; transportation cost accounts for relevant fraction of total investment	Between 10 kg and 100 kg; extremely easy to transport (package occupies small space)	Between 50 kg and 200 kg; easy to transport (can be dismantled)
Mechanical property	Good	Easily damaged	Good
Insulation	Normal; easily influenced by ambient temperature	Normal, easily influenced by ambient temperature	Good with low coefficient of heat conductivity
Tightness	Bad; requires skilled workmanship for sealing	Depends on material properties; easy to repair in case of leakage	Good; resistant to acid corrosion
Water absorption rate	High; corrodes easily under high underground water level	Low; suitable for regions with loosen soil and high underground water level	Low; suitable for regions with high underground water level

Source: Zheng et al. (2020)

A summary of South Africa's experience with various biogas constructions is given in Table 3 (extracted from the marketing report for this project).

[10] BOD = biological oxygen demand and is indicative of the biological nutritive value of the feedstock

Table 3. Summary of micro-scale digesters in South Africa

	Brick and mortar fixed dome digester	Floating drum digester	Balloon/bag Digester	Underground digester $10m^3$ (AGET)	Portable digester $2.5m^3$ (AGET)	Fixed dome digester (EZ-Digester)	The Little green monster	Moulded fixed dome (AGAMA)	In-situ cast concrete digester (Puxin patent)
Size (volume)	$4\text{-}20m^3$	$1.2\text{-}15\ m^3$	$15m^3$	$10m^3$	$2.5m^3$	$1.5m^3$	$2.5m^3$	$6m^3$	$10m^3$
Gas output/ day	Varies	Varies	$5m^3$	$8m^3$	$2m^3$	Not available	$2m^3$	$2m^3$	$3\text{-}5m^3$
Feedstock	Varies Manure, organic waste	Varies Manure, organic waste	200kg Manure, organic waste	120kg Manure, organic waste,	5-8kg Organic waste	25kg Organic waste	Organic waste	40kg Manure, organic waste	80-100kg Manure, organic waste,
Cost	Up to R60000	Up to R60000	Up to R60000	Not provided	Not provided	R12000	Not provided	Not provided	R60000
Main Materials	Brick and mortar	Steel	PVC Insulation required to maintain temperature.	Concrete (digester) Plastic (biogas bag)	Plastic.	Plastic, moulded. Portable.	Polyethylene plastic, moulded.	Plastic	Steel, concrete, fibre glass
Expected life	3 years	8 years	15 years	Not provided	Not provided	10 years	20 years	Not provided	30 years
Installation and operation	Excavation required. Gas at variable pressure – inefficient for equipment.	Excavation required. Simple operation. Monitor for fibrous materials.	Easy to install. Excavation required. Constant monitoring of slurry level. Slurry dilution when rains.	Excavation required. Portable biogas bag for indoor use.	Mobile Includes integrated photovoltaic module for gas pump.	Prefabricated. Above ground. No temperature controls. Manual agitation required.	Prefabricated. Excavation required.	Prefabricated. Above ground.	Excavation required.
Maintenance	Cracks and gas leaks are common. Ground may also destabilise.	Corrosion of steel parts and sliding mechanism.	Slope distortion needs to be monitored. Fails due to lack of agitation.	Not provided	Not provided	Prone to clogging, ongoing maintenance.	Maintenance to remove soli sludge.	Maintenance for cleaning.	Easy to clean.

Source: DIFD 2011; Mutungwazi 2018; Rajendran 2012

Benefits of Biogas

There are a number of important benefits from the use of micro digesters (Jain et al., 2019). Although a full discussion of the benefits is outside the scope of this study, recognition of the various aspects is necessary to valorise or monetise the credits from the use of the digesters. A partial listing of the benefits includes the following:

For farms:

- improved nutrient utilization from manure, reduce odour nuisances, use of surplus heat for drying grains, or improved possibilities to export surplus fractions of treated digested manure as well as mitigation of CH4 and NH3 emissions from stables and manure storage

For homeowners:

- an energy source for cooking and heating
- liquid fertiliser (digestate)

However, it is noted that the claims that domestic biogas can significantly contribute to the "ambitious goal of ensuring universal access to modern energy services by 2030" (Ortiz et al., 2017) are perhaps unlikely given the operational difficulties. The experience of countries with high levels of digester installation, such as India and China, is that the rate of abandonment of micro-digesters is between 30% to 60% (Ortiz et al., 2017). The high levels of failure are ascribed to poor training, limitations in feedstock, weak user commitment, and under-performance of the cooking facilities (Ortiz et al., 2017).

Techno-Economics of Biogas

The techno-economics of biogas have been evaluated in multiple studies over a large number of geographic contexts, feedstocks and technologies (Mkhabela et al., 2020; Khan et al., 2014; Akbulut, 2012). The results of these studies are summarised in Table 4.

Table 4. Summary of biogas techno-economic assessments

Type of Digester	**Study**	**Country**	**Volume (m^3)**	**Capital Cost (USD/m^3)**	**LCOE (USD/MWh)**
Tube	Khan et al. (2014)	Bangladesh	150	120	15 to 30
Fixed Dome	Mkhabela et al. (2020)	South Africa	12	100	275
Tube	Kost et al. (2018); Putti et al. (2015)	Tanzania and India	20 - 50	350 - 750	170
Bag	Cheng et al. (2014)	Global	>25	20 - 200	120
Fixed Dome	Cheng et al. (2014)	Global	>25	300 - 800	180
Composite Material	Cheng et al. (2014)	Global	>25	100 - 300	140
CSTR	Jarrar et al. (2020)	Jordan	419	150	100

Three methodologies are being applied in assessing the financial viability of biogas, namely discounted cash flow-net present value (DCF-NPV), discounted payback period (DPP) and levelized cost of energy (LCOE) or levelized cost of cooking (LCOC) (Putti et al., 2015).

DCF-NPV is the most common measure, widely applied in the techno-economic assessment of potential investments with a clear output (such as a product or service) and a range of input measures whose values can either be estimated from the process information or at least applied based on a relevant set of standard assumptions.

DPP is not widely used due to its weak link to company financial statements and the lack of comparable information.

LCOE/LCOC is useful in comparing biogas as a cooking fuel relative to other sources of primary energy used for food preparation. The technique is based on the following formula:

$$LCOE = \frac{Discounted\ Value\ of\ Sum\ of\ Costs\ over\ Lifetime\ of\ Energy\ System}{Discounted\ Value\ of\ Sum\ of\ Energy\ Produced\ over\ Lifetime}$$

$$= \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

and

$$LCOC = LCOE * Cooking\ Use$$

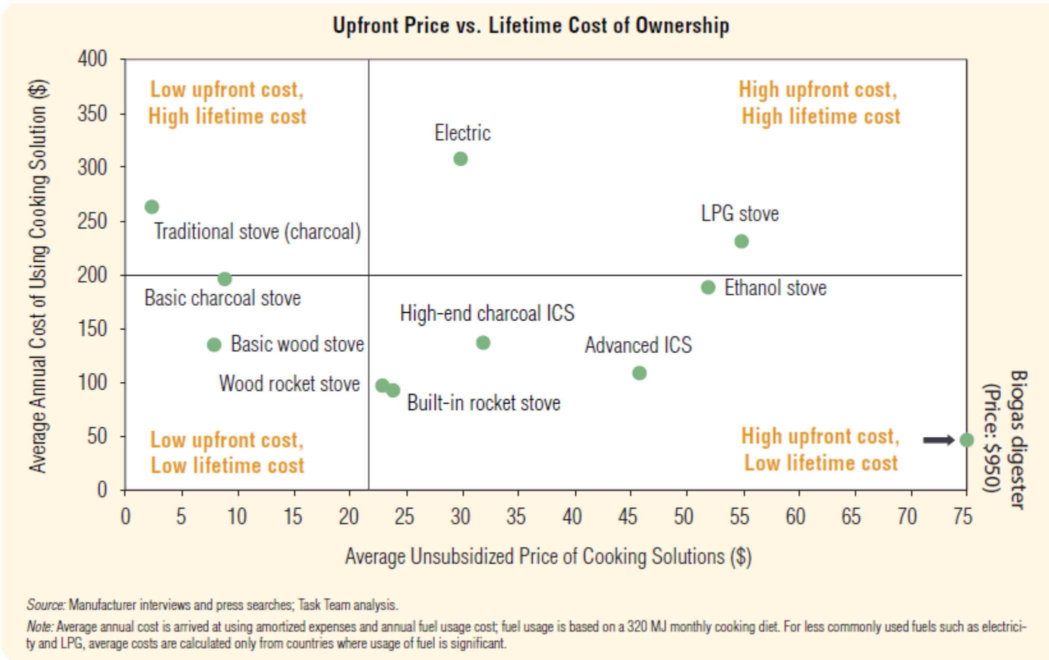
where:

I_t	= investment expenditure in year t (USD)
$O\&M_t$	= operational and maintenance expenditures in year t (USD)
F_t	= fuel expenditure in year t (USD)
E_c	= minimum cooking energy (320 MJ/month * 12 months/year)
E_t	= energy output in year t (kWh)
r	= discount rate
n	= expected lifetime of the system
Cooking Use	= 320 MJ per year

Typical values for LCOC vs initial costs for the cooking equipment are shown in Figure 2 (Putti et al., 2015). It is noted that a biogas generator connected to a gas ring has a high upfront cost but a low operating cost, meaning that the overall LCOC is one of the lowest-cost technologies for cooking. This point is confirmed by the results of this study, as discussed in Section 0. (The calculation ignores the energy loss of the stove.)

Given that all of the digesters in the SANEDI study are being used to produce biogas for cooking food and not for space heating or the generation of electrical energy, it is logical to apply the LCOC approach in this study. Moreover, there are no revenue streams at the SANEDI sites, making the application of discounted cash flow-net present value (DCF-NPV) less useful or relevant. Further details on the methodology of the evaluation are now presented.

Figure 2. LCOC vs upfront price of cooking equipment



Source: Putti et al. (2015)

Methodology

In this assessment, two overlapping techno-economic approaches have been used, LCOE/LCOC and DCF-NPV. Common to both methods is a set of input assumptions necessary for the models, as shown in Table 5.

Table 5. Input assumptions for techno-economic models

Output	Units	Value	Reference
Gas Output	m3/d	50% of capacity	Mutungwazi et al. (2018)
Biogas Calorific Value	MJ/m^3	24	Khan et al. (2014)
Gas Cost	ZAR/kWh	1.015	eGoli Gas (2021)
LCOC Value	MJ/month	320	Putti et al. (2015)
Thermal Efficiency	%	60.7%	Lather (2019)
Project Lifetime	years	10	N/A
Exchange Rate	ZAR/USD	15	Current Value (March 2021)
Working Average Cost of Capital	%	10	Current Interest Rate

LCOE requires measured or at least estimated data for gas output, capital cost, operations and maintenance cost, and variable cost. The way the values for these parameters were obtained is described in more detail in Section 0.

LCOC is calculated by multiplying the LCOE by the annual cooking energy requirement. The latter is set as 320 MJ/year (Putti et al., 2015). Values for LCOC vary from USD 50 to USD 350, depending on the type of stove and the fuel source, as shown in Figure 2.

Results – Cost of Biogas

The field work was initially intended to cover the micro digesters in all three provinces, which have SANEDI-supported micro-digesters (Limpopo, KwaZulu Natal and Gauteng), consisting of more than a hundred installations using a variety of technologies, designs and feedstocks. However, several issues resulted in delayed visits to the sites in KZN, and therefore this analysis has relied on data from the survey of 35 facilities in Limpopo (31) and Gauteng (4).

The field work revealed that of the 35 digesters, only 22 were still functional, and even this group were functional to a limited extent. As a result, it was decided not to attempt a techno-economic review based on all the sites but instead to choose two high-performing (high on-stream functionality) units, namely the biobag digester in Sharpeville and the fixed dome digester in Chavani. A summary of the relevant results from the field work for these two sites, which offered the most complete datasets covering the capital cost, the operating costs and the biogas benefit, and could be used as the input values to the assessment, are shown in Table 6.

Table 6. Input values for the assessment for the two high-performing installations

Generation Technology/ Primary Raw Material	**Units**	**Biobag (Sharpeville)**	**Fixed Dome (Chavani)**
Size	m3	15	12
CAPEX	ZAR/m3	8,636	4,782
Fixed Cost	% of CAPEX	5%	
	ZAR/kW/year	3,109	1,721
Variable Cost	ZAR/kWh	0.00	
Capacity Factor	%	80%	
LPG Savings	ZAR/year	8,400	

Even for these two sites, it was necessary to estimate many of the input values, such as the maintenance cost, the variable cost, the rate of gas production, the capacity factor and the accrued benefits to the users. Maintenance was being undertaken by SANEDI and/or its contracted partner at no cost to the digester owner for some of the digesters. However, several digesters had not been maintained at all. The variable costs, mostly connected to the direct labour for the loading of feedstock, were not proportioned, other than to note that a hired technician was being employed or that the task was being completed by kitchen staff. Gas production was not measured in any of the facilities, and hence the rate was assumed to be 0.5 m^3 biogas/m^3 digester/day, which is an average value for the feedstocks being used. The capacity factor was estimated at 80%.

Benefits accrued for each site were taken from the average values across all the digesters. For well-maintained sites, the derived value was mentioned as the equivalent of one 19 kg cylinder of LPG per month, equating to about 950 MJ. Based on the estimated values from Table 6, such a saving is about 40% to 50% of the potential biogas output, suggesting that there is significant excess gas or that the digesters are operating at a lower productivity than quoted in the specifications.

Capital Costs

The capital cost for the Chavani digester could not be confirmed at the time of the survey. As a result, the value of ZAR 57,383 for a 12 m^3 fixed dome, brick and mortar structure, taken from Mkhabela et al. (2020), was used. For the biobag digester, the installed cost, as invoiced to SANEDI by the supplier, of ZAR 129,537 for a 15m^3 bag was used. In dollar terms, these values are about USD 300 per m^3 and USD 500 per $m^{3,}$ respectively.

The global average for capital cost is highly variable, as shown in Table 3, depending on the design, location, and size. However, the two values used in this study fall within the global averages and seem reasonable, although the cost of the biobag appears high for a prefabricated micro digester.

Operating, Variable and Maintenance Costs

Operating and variable costs for micro digesters include the labour cost of loading feedstock and any water requirement for which a direct payment must be made (it is generally the case that the primary feedstock is a waste material for which no payment is necessary). For the purposes of this study, and in the absence of any detailed information from the field study, it was assumed that operating and variable costs are zero.

As already mentioned, maintenance costs for the two sites were not available. Therefore, based on the general practice, it was assumed that the maintenance costs (per annum) are 5% of the capital cost (Khan et al., 2014).

Levelised Cost of Energy, Cost of Cooking and Net Present Value

The results of the assessment are shown in Table 7.

Table 7. TEA Results for the two high-performing installations (80% capacity utilisation)

Output	**Units**	**Fixed Dome (Chavani)**	**Biobag (Sharpeville)**
Equivalent Energy Output	MJ/month	3,504	4,380
LCOE	ZAR/kWh	1.086	1.908
	USD/MWh	72	127
LCOC	USD/year	77	136
NPV	ZAR	-14,368	-73,554

The estimated energy output for the Chavani and Sharpeville digesters are 3,500 and 4,400 MJ per month, respectively. These values are about 10 times the minimum energy required for cooking based on the literature value of 320 MJ per month, but comparable to the energy demand of a school kitchen, which, based on the results from the fieldwork linked to this study, is reported to be 2 of 19 kg LPG cylinders per month, or about 1,900 MJ per month. In other words, the digesters are well-suited to supply kitchens of public facilities such as schools and community centres.

The LCOEs for each site (Chavani and Sharpeville) are ZAR 1.09 per kWh and ZAR 1.91 per kWh, respectively (USD 72 and USD 127 per MWh). Both values are lower than the present price of LPG, as supplied in a 19 kg cylinder, of ZAR 2.80 per kWh, and the standard pay-as-you-go tariff for electricity in urban areas of about ZAR 2.50 per kWh. However, the values are higher than literature values for the LCOE of biogas in other countries, which range between USD 50 and USD 200 per MWh, as shown in Table 4.

Similarly, the LCOC values for the two sites of Chavani and Sharpeville are calculated as USD 77 and USD 136, respectively (ignoring the energy loss of the stove). These values are similar to the literature value of USD 50, as already reported in Figure 2.

Finally, the NPVs, calculated on the basis of a net credit to a saving in LPG expenses, are – ZAR 14,400 and – ZAR 73,554, respectively, indicating that neither site is viable based on the present performance and assumptions.

Gas Output at One Cylinder LPG per Month

All the results in the preceding sections depend on the single assumption that the gas output is 80% of the design capacity for the micro digesters. However, it is likely that this capacity utilisation is not achieved. Reports from the field work indicate that a functional digester can replace the use of one 19 kg LPG cylinder per month, equivalent to a gas energy output of 950 MJ.

It is possible to model this output for each digester; the results are shown in Table 8. NPV is unchanged since the excess output in the base case was not converted to revenue, and hence the costs/revenues remain the same for both simulations. However, the LCOE and LCOC values are more than double due to the lower capacity utilisation (about 20% vs 80%) and the reduced output of biogas per day.

Table 8. TEA Results for the two high-performing installations (output at 1 LPG cylinder)

Output	**Units**	**Fixed Dome (Chavani)**	**Biobag (Sharpeville)**
Capacity Factor	%	22%	17%
Equivalent Energy Output	MJ/month	950	950
LCOE	ZAR/kWh	4.005	8.795
	USD/MWh	267	586
LCOC	USD/year	285	625
NPV	ZAR	-14,368	-73,554

Discussion

Despite several decades of experience in technology, many programmes covering the installation and maintenance of digesters depend on government grants and incentives (Surendra et al., 2014). In developed countries, biogas from agricultural waste is converted into electricity and heat, with subsidy schemes encouraging electricity production through sale to the grid or substitution behind-the-meter energy consumption. In developing countries, the subsidies tend to cover the capital cost of installation.

In other words, biogas technology is generally not feasible except in situations where the facility has access to large volumes of a nutrient-laden feedstock such as abattoir or piggery waste and/or there is a government subsidy for the programme in the form of a direct financial grant.

A similar result was obtained in this study. Based on the operating values for the two highest-performing micro digesters within the SANEDI sites, assuming that each site has a gas output equivalent to one 19 kg LPG cylinder per month, the LCOE values are between 1.5 and 4 times the cost of grid-based electricity or bottled gas. The annualised costs of the Chavani digester are about half those of the Sharpeville facility due to the lower capital cost of the fixed dome structure relative to the biobag. NPV values for both sites, regardless of the assumption in terms of capacity utilisation, are negative.

The results of this study contradict the earlier publications of South African biogas digesters, for which more positive NPV estimates are reported (Mkhabela et al., 2020; Masebinu et al., 2018; Mutungwazi et al., 2018). In the author's view, these studies make overly optimistic assumptions about the long-term performance of the digesters in the field and hence obtain a positive return on investment.

The challenges for establishing viable micro digesters are multiple. Some of the key issues are as follows:

- the waste, used as the feedstock for the micro digester, and the user of the biogas, need to be in close proximity. For instance, a farm that uses animal manure as feedstock must be able to convert the biogas to heat or electricity on site. Most of the SANEDI-supported facilities are mismatched in this sense. Sufficient feedstock may be some distance from the digester, located close to a school or public utility which can use the biogas for cooking.
- The successful operations and maintenance of a micro digester are non-trivial. The staff responsible for the facility need to be properly trained in the technology and be able to maintain the digester in the event of a process failure.
- All the outputs from the digester need to be fully utilised, including the total gas output and the digestate. The latter has considerable value as a fertiliser but has not been included as a credit in this assessment, nor is there any indication from the study's fieldwork that it is being used productively.
- Similarly, other benefits of the digester could be included in such assessments if the value thereof can be proportioned. Examples include savings associated with reduced waste water or sewerage treatment, lower refuse removal costs, and reduced fertiliser usage.
- Even the smallest SANEDI-supported digester has the potential of a large output of biogas, perhaps 5 to 10 times the requirement for gas as a means of cooking in a small home. Matching the demand for gas with the available feedstock, and sizing the micro digester appropriately, appears to have been largely overlooked in this programme.

Conclusion

The objective of this study has been to evaluate the economic feasibility of the SANEDI programme in micro digesters over the last five years. The programme has been considerable in its scope, supporting more than 100 digesters in three provinces using various technologies and sizes. Due to limitations in the consistency or availability of input values for the techno-economic models, the evaluation has focused on two key installations for which most of the data is available. The facilities themselves have a high level of on-stream functionality (producing biogas). The two selected generators are the fixed dome digester at Chavani and the biobag digester in Sharpeville.

Assuming that the digesters have been operating consistently at 80% of the design output, the LCOE and LCOC values were found to be close to the previously reported value in other countries and lower than the cost of alternative energy sources, including electricity and biomass. However, it appears that this actual gas output has been only 20% of the design level, making the LCOE and LCOC values between 1.5 and 4 times the cost of either grid-based electricity or bottled LPG. Similarly, both projects have a negative NPV.

The analysis suggests various ways in which the economic returns can be increased, such as obtaining the full benefit from the biogas and the digestate, maintaining an adequate supply of feedstock, improving support and training for the digesters' operators and finally correctly proportioning all the externalities of the programme.

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Annex 3: Market analysis

BACKGROUND

This document forms part of a set of reports that together comprise an assessment of the South African National Energy Development Institute's (SANEDI) micro-scale anaerobic biogas digester programme. Their primary purpose, as a collective, is to facilitate a sectoral development plan, support the development of a micro-scale anaerobic biogas digester industry, and promote the widespread deployment of these technologies in South Africa. The purpose of this report is to provide an overview and analysis of the market potential for micro-scale anaerobic biogas digesters in South Africa.

SANEDI MICRO-SCALE ANAEROBIC DIGESTER PROJECT

"SANEDI has promoted the micro-digester project under the Working for Energy programme to provide sustainable clean energy solutions to rural and low-income urban communities with special emphasis on job creation, skills development and community enterprise development" (UJ-PEEETS 2020, p. 9). The project has been promoted as providing an alternative source of energy for cooking by converting organic matter and animal manure to biogas through the process of anaerobic digestion in micro-scale digesters.

METHODOLOGY

The market potential for a product or technology is a function of a target market's size and the product's estimated penetration rate into that market. This report draws on international, regional and national literature and national economic and socio-economic data to estimate the size of the identified target market segments. Academic literature, international and national economic data, and primary data obtained from field research on SANEDI's micro-scale digesters programmes were referenced to establish factors that impact the penetration rate estimations. A number of penetration rate scenarios are then presented and applied to each market segment, and their implications for market potential are discussed.

INTRODUCTION

This document's focus is directed towards addressing two research questions. First, what factors are likely to impact the development of a sustainable market-based biogas micro-digester industry to realise this potential? Second, what is the likely market potential for micro-scale anaerobic biogas digesters in South Africa? The two objectives associated with these questions are

i. To identify critical factors that will influence the future development of a sustainable market-based industry.

ii. To estimate the potential size of the market for micro-scale anaerobic biogas digesters in South Africa.

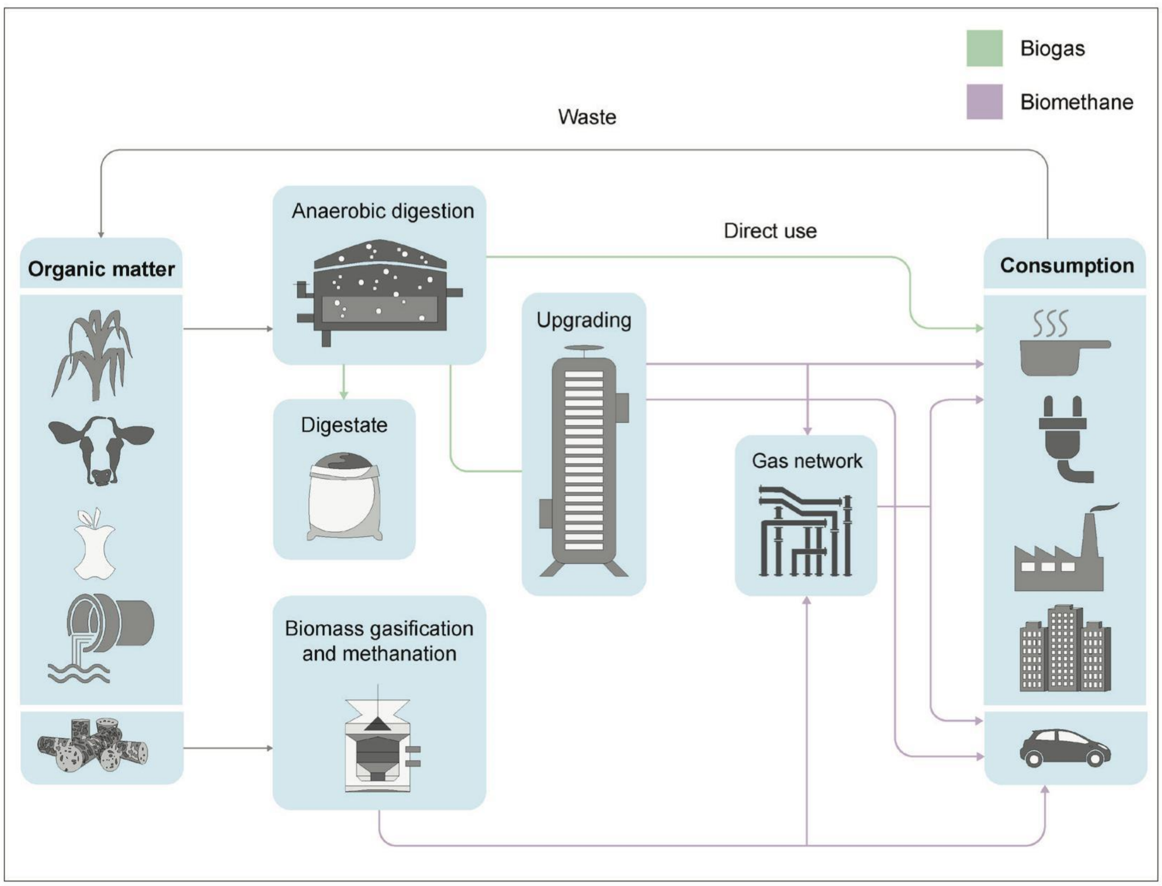
The report is structured as follows. First, a brief overview of biogas as a sustainable bioenergy source is presented, including production pathways, the motivations for the technology's deployment, and key industry metrics about current production in South Africa. Section 2 introduces the micro-scale digester niche, including international deployment and known micro-scale digester designs marketed in South Africa. The following section delineates the potential target market and market segments and estimates market segments' sizes. Section 4 summarise and analyses the key factors impacting technology deployment and indicates their likely impact on penetration rates. Section 5 discusses each segment's market potential, and Section 6 concludes with recommendations for further research and action.

BIOGAS AS SUSTAINABLE BIOENERGY: AN OVERVIEW

BIOGAS PRODUCTION PATHWAYS

The International Renewable Energy Agency (IRENA) describes biogas as "a modern form of bioenergy that can be produced through anaerobic digestion or fermentation of a variety of biomass sources." (IRENA 2017, p. 6)". As Joshi et al. (2017, p. 851) explain, the anaerobic digestion of organic materials generates biogas through the biodegradation of organic matter, which occurs in the absence of oxygen. Technologically, biogas production is well-established, and the production pathways are well understood (Great Britain. Department for International Development (DFID) 2011). Like natural gas, biogas can be used for heating, electricity generation, and even fuel for vehicles if suitably upgraded (Figure 1).

Figure 3. Biogas and biomethane production pathways*



Source: Reproduced from IEA (2020, p. 5)

*Biogas comprises methane (60%), carbon dioxide (40%) and other trace gases. Biomethane is pure methane and can be produced separately or from upgraded biogas, where carbon dioxide and other trace contaminants are removed.

Several types of biomass or organic matter are suitable for digestion. Organic matter – referred to as feedstocks in the production process – can be sourced from animal manure, crop residue, and human waste (IEA 2020; Jordaan 2018). Various types of plants are also available, categorised according to size as either large- or small-scale (DFID 2011; IRENA 2017). Terms classifying small-scale biogas plants are often derived from the type of consumer or end-user; domestic, residential, household, decentralised, farm and communal (IEA 2020) are all used in research. In this report, the term micro-scale anaerobic biogas digester denotes small-scale plants with a power supply capacity of less than 30kW[11] for cooking, lighting or sanitation.

THE CASE FOR BIOGAS AS SUSTAINABLE BIOENERGY

The International Energy Agency (IEA) positions the case for biogas at the "intersection of two critical challenges of modern life: dealing with the increasing amount of organic waste that is produced by modern societies and economies, and the imperative to reduce global greenhouse gas (GHG) emissions" (IEA 2020, p.3). Indeed, as Kruger and McCauley (2020, p. 102) point out, human settlements produce the resources (feedstocks) for biogas as a matter of course. Methane emitted from waste, agriculture and industry accounts (referred to as anthropogenic methane emissions) accounts for almost 50 per cent of the total global emission (Nevzorova and Kutcherov 2019). Anaerobic digestion of these feedstocks can provide a sustainable bioenergy source that does not compete with food or results in biodiversity loss (Nevzorova and Kutcherov 2019). The IEA estimate that harnessing these feedstocks as a source of bioenergy could replace some 20% of existing worldwide gas demand (IEA 2020, p. 6) while supporting the decarbonisation of sectors unable to access low-carbon electricity.

For developing and marginalised countries, biogas from sustainable feedstocks is touted as an essential pathway to address a third critical challenge. Encapsulated in the United Nations (UN) Sustainable Development Goals (SDG), Goal Seven is to "ensure access to affordable, reliable, sustainable and modern energy for all" (United Nations 2018, p. 11). Biogas produced from micro-digester units offers considerable health, social and economic benefits by providing a valuable, sustainable source of clean energy for power, heat and cooking (DFID 2011; IEA 2020; IRENA 2017), particularly when displacing traditional biomass such as charcoal or firewood. These benefits are particularly pertinent in countries with weaker or less accessible power grids and intermittent electricity supply (United Nations 2018). Other opportunities listed by the Department of Energy (DoE) (n.d.) include its potential as a cheaper alternative to liquid fuels for vehicles, the nutrient-rich fertiliser by-product of the production process, job creation and skills development.

BIOGAS PRODUCTION IN SOUTH AFRICA

The introduction of biogas technology into South Africa refers to the first plant constructed in 1957, producing biogas from pig manure (Mutungwazi et al., 2018). As a leading renewable energy-generating country in Africa, South Africa is now the top producer of biogas, contributing 61% of African capacity in 2016 (Sanusi and Spahn 2020, p. 278). Much of this contribution may be attributed to larger producers with a supply capacity of between 30kW and 19MW. Literature references approximately 700 digesters have been installed since 1957, although no definitive number is available to date (Mutungwazi et al.,

[11] The categorisation of micro-scale digesters is not applied consistently in research. For example, Mutungwazi et al. (2018) consider the term applicable to plants producing less than 25kW per hour.

2018). Kemausuor et al. (2018) refer to as few as 300 in operation in 2017, with 90% classified as micro-scale. Makumba et al. (2016) cite 200 in operation. Mutungwazi et al. (2018, p. 173) refer to the installation of "several hundreds of small domestic scale digesters", of which there is no precise record of their number. Notwithstanding South Africa's leading role, domestic production and consumption of biogas as sources of energy are considered lagging behind the rest of the world (Jordaan 2018; Makumba et al. 2016). Germany, for example, is a world leader, with more than 7000 digester plants, constructing four new biogas plants daily (Makumba et al., 2016).

MICRO-SCALE DIGESTER TECHNOLOGY

The micro-scale digester technology services one niche of the biogas sector, providing a potentially sustainable bioenergy source on a small scale for heating, lighting and cooking. IRENA (2017, p. 18) cites some 50 million biogas systems are providing energy for cooking, primarily in India and China. However, "Estimating the use of residential-scale biogas for cooking in developing countries is challenging because biogas digester units often are locally sourced, and the resulting energy provision is rarely measured" (IRENA 2013, cited in IRENA 2017, p.18). Several countries are implementing and piloting programmes to develop local micro-scale industries to harness the environmental, socio-economic and developmental benefits of facilitating biogas as a clean energy source (DIFD 2011; IRENA 2017, p. 20). Pilot installations in energy-deprived or energy-insecure households and communal spaces are often supported by government subsidies and international development agencies concerned with achieving SDG goals (DIFD 2011). The number of units varies significantly across countries and regions (Table 1).

Notwithstanding the unaccounted installations Mutungwazi et al. (2018) refer to, the estimated number of small-scale digester units in South Africa lags several developed and developing nations (Table 1), including, when considered per household basis, indicating opportunities for greater domestic market penetration for micro-scale units. For example, 486 million Chinese households in 2020 (Euromonitor International 2021) places market penetration at around 9% (assuming that all micro-digesters are installed in households). With a 2020 population of around 97 million, comprising 21 million households, Vietnam has a domestic penetration per household of about 0.9%. Kenya's population of 53.7 million in 2020 is more comparable to South Africa's 59.6 million (Statistics South Africa (StatsSA) 2020a). Kenya had an estimated 11.8 million households in 2020 (Euromonitor International 2021), placing domestic penetration at around 0.2%. Based on an estimated 16.67 million households (StatsSA 2018), if 90% of 300 operational digesters are micro-scale, South Africa's approximate penetration is a minuscule 0.0016%.

The varying success of micro-scale digester installation programmes (DIFD 2011), and the different penetration levels reached, suggests that harnessing this technology's potential is materially contingent upon local conditions and contexts. Researchers have found that financial, sociological, institutional, and environmental factors, *inter alia*, are all critical considerations (e.g. DFID 2011; Jordaan 2018; Nevzorova and Kutcherov 2019). Furthermore, as the DIFD (2011) conclude, the primary challenge is likely not to develop micro-scale digester technology but rather to overcome challenges to support its adoption and deployment in contexts characterised by significant financial and other resource constraints. A comparison of digesters across selected regions and countries reveals the comparatively high cost of micro-scale units in South Africa (Table 2).

Table 9. Micro-scale digester units in selected countries, 2014

Region/Country	Number of units
Asia	
China	43 000 000
India	4 750 000
Nepal	330 000
Viet Nam	182 800
Bangladesh	37 060
Cambodia	23 220
Indonesia	15 890
Pakistan	5 360
Laos	2 890
Bhutan	1 420
Africa	
Kenya	14 110
United Republic of Tanzania	11 100
Ethiopia	10 680
Uganda	5 700
Burkina Faso	5 460
Rwanda	1 700
Cameroon	300
Benin	110
Latin America	
Bolivia	500
Nicaragua	280

Source: Reproduced from IEA (2020, p. 5)

Table 10. Small-scale (domestic) biogas digester unit costs, selected regions and/or biogas digester types

Region/country, type	Cost per unit (USD)	Source
Asia, biogas digester	612	REN21, 2015
Africa, biogas digester	886	REN21, 2015
China, domestic biogas digester	368–792	Zuzhang, 2014
India, PBD Sintex Industries	350–750	Putti et al., 2015
United Republic of Tanzania, PBD SimGas	350–750	Putti et al., 2015
South Africa, PBD Agama Biogas	2 800	Cheng et al., 2014
World, bag digester	20–200	Cheng et al., 2014
World, composite material digester (CMD)	100–300	Cheng et al., 2014
World, household biogas plant and stove	500–1 500	Putti et al., 2015
World, onsite-constructed digester (OCD)	300–800	Cheng et al., 2014

Source: Reproduced from IRENA (2017, p. 23)

MICRO-SCALE DIGESTER DESIGNS

IRENA (2017) have identified three main types of micro-scale digesters in operation internationally: the fixed-dome plant, the floating drum plant, and the balloon/bag digester. Literature also references a fourth – the plug-flow tube digester (UJ-PEETS 2020, p. 18). All appear to be are operational in South Africa, along with several proprietary modified designs developed by private companies. The various digesters represent various capacities, feedstock volume requirements, gas outputs, expected life metrics, and maintenance and operational requirements. Table 3 presents available metrics on the different micro-scale digesters marketed in South Africa, including size and energy output, materials used, and expected life. Appendix B shows diagrams and images of the unit designs.

From a product perspective, a distinction can be drawn between prefabricated and built digesters. Built digesters require excavation and construction onsite. Due to poor construction, they are prone to quality issues (DIFD 2011; Mutungwazi 2018) but offer better rural job creation and skills development opportunities (UJ-PEETS 2020).

Table 11. Micro-scale digesters marketed in South Africa

	Brick and mortar fixed dome digester	Floating drum digester	Balloon/ bag Digester	Under-ground digester 10m³ (AGET)	Portable digester 2.5m³ (AGET)	Fixed dome digester (EZ-Digester)	The Little Green Monster	Moulded fixed dome (AGAMA)	In-situ cast concrete digester (Puxin patent)
Size (volume)	4-20m^3	1.2-15 m^3	15m^3	10m^3	2.5m^3	1.5m^3	2.5m^3	6m^3	10m^3
Gas output/ day	Varies	Varies	5m^3	8m^3	2m^3	Not available	2m^3	2m^3	3-5m^3
Feedstock	Varies Manure, organic waste	Varies Manure, organic waste	200kg Manure, organic waste	120kg Manure, organic waste,	5-8kg Organic waste	25kg Organic waste	Organic waste	40kg Manure, organic waste	80-100kg Manure, organic waste,
Cost	Up to R80000	Up to R60000	Up to R60000	Not provided	Not provided	R12000	Not provided	Not provided	R60000
Main Materials	Brick and mortar	Steel	PVC Insulation required to maintain temperature	Concrete (digester) Plastic (biogas bag)	Plastic.	Plastic, moulded. Portable.	Polyethylene plastic, moulded.	Plastic	Steel, concrete, fibreglass
Expected life	3 years	8 years	15 years	Not provided	Not provided	10 years	20 years	Not provided	30 years

Table 3. Micro-scale digesters marketed in South Africa continued

	Brick and mortar fixed dome digester	Floating drum digester	Balloon /bag Digester	Under-ground digester $10m^3$ (AGET)	Portable digester $2.5m^3$ (AGET)	Fixed dome digester (EZ-Digester)	The Little Green Monster	Moulded fixed dome (AGAMA)	In-situ cast concrete digester (Puxin patent)
Installation and operation	Excavation required. Gas at variable pressure – inefficient for equipment.	Excavation required. Simple operation. Monitor for fibrous materials.	Easy to install. Excavation required. Constant monitoring of slurry level. Slurry dilution when it rains.	Excavation required. Portable biogas bag for indoor use.	Mobile Includes integrated photovoltaic module for a gas pump.	Prefabricated. Above ground. No temperature controls. Manual agitation is required.	Prefabricated. Excavation required.	Prefabricated. Above ground.	Excavation required.
Maintenance	Cracks and gas leaks are common. The ground may also destabilise.	Corrosion of steel parts and sliding mechanism.	Slope distortion needs to be monitored. Fails due to lack of agitation.	Not provided	Not provided	Prone to clogging, ongoing maintenance.	Maintenance to remove soli sludge.	Maintenance for cleaning.	Easy to clean.

Source: DIFD 2011; Mukumba et al. 2016; Mutungwazi et al. 2018; UJ-PEETS 2020; Rajendran 2012

Therefore, built digesters have been marketed as suitable for rural households that own livestock, producing sufficient manure to feed the digesters. Prefabricated digesters, which are moulded from plastic, generally have longer life spans and require less feedstock. These digesters are more compact and can likely be used by a more diverse set of consumers if sufficient organic material is available. The market potential for a specific type of digester will thus necessarily be dependent upon specific product-related factors, including feedstock suitability, expected life, ease of use and maintenance, and gas output. "The choice of the design of the digester is thus a key determinant in the feasibility of its implementation" (DIFD 2011, p. 7).

MARKET SEGMENTS

Reviewing the literature on micro-scale digesters, we identified three target markets, broadly grouped into households, communal spaces and institutions, and hospitality establishments (DIFD 2011; IRENA 2017; Thiriet 2020). Households can be further segmented into rural and urban households, electrified and without electricity access. Community institutions include schools, nursing and care homes, and other community-orientated centres. The hospitality segment includes wine, game and bush farms, and restaurants and public and private canteens.

HOUSEHOLDS

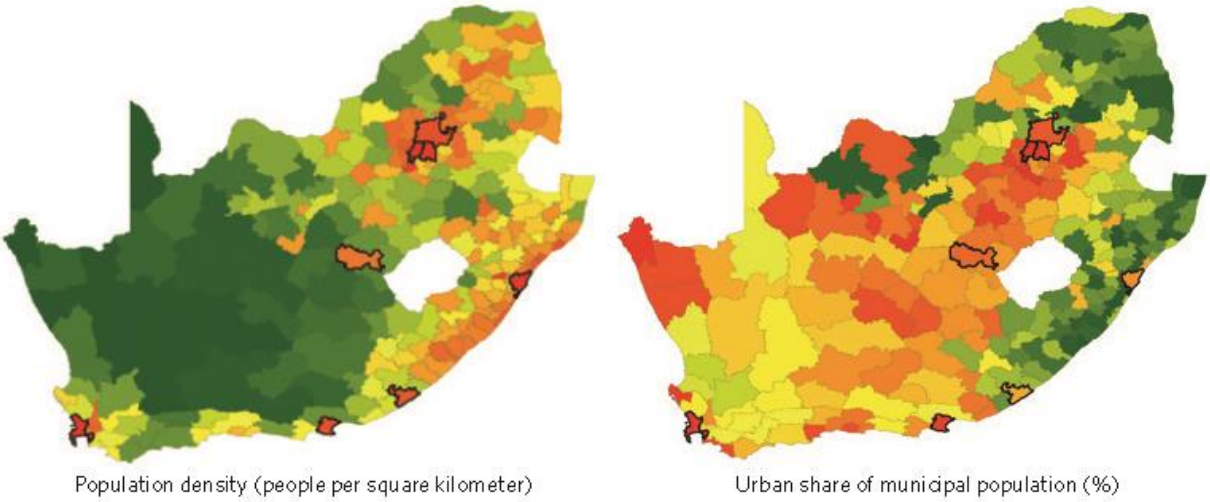
Theoretically, households represent the most significant potential target market for micro-scale digesters in terms of volume. The most recent General Household Survey, 2018, estimated some 16.7 million households in South Africa, constituting a population of approximately 57.5 million. Gauteng Province has the largest number of households, while 58% of households are concentrated in the largest three provinces: Gauteng, KwaZulu-Natal, and Western Cape. The estimated population and household distribution of provinces are presented in Appendix B.

This market can be further segmented between rural and urban households. Rural households are typically larger, where 20.6% have six or more members, and 24.3% have 4-5 members (Appendix B). Approximately 79% of rural households also own livestock that produces manure (UJ-PEETS 2020). Rural segments arguably offer more significant socio-economic and environmental benefits for recipients. In addition to the environmental reductions to GHG emissions, these households would also benefit from the displacement of energy derived from traditional solid biomass fuels, such as less time gathering firewood and reduced air pollution indoors.

However, most of the country's population is concentrated in urban areas (Figure 2) governed by urban municipal authorities (Figure 3). A 2016 estimate placed 91% of South Africa's population in these urban regions (Arndt et al. 2018) (Appendix B). While the initial focus of many pilot projects in South Africa (and, indeed, internationally) has been on rural households, urban households all represent potential customers of micro-digesters. For market segmentation, a further differentiation between city and peri-urban[12] households may be helpful. Factors such as rising urban poverty (Arndt et al. 2018), coupled with the increased cost of waste management in urban areas (Thiriet et al. 2020), has prompted the consideration of networks of micro-scale digesters as part of decentralised urban and peri-urban waste management (Figure 4).

Figure 4. Municipal Population Densities and Urbanization Rates, 2011

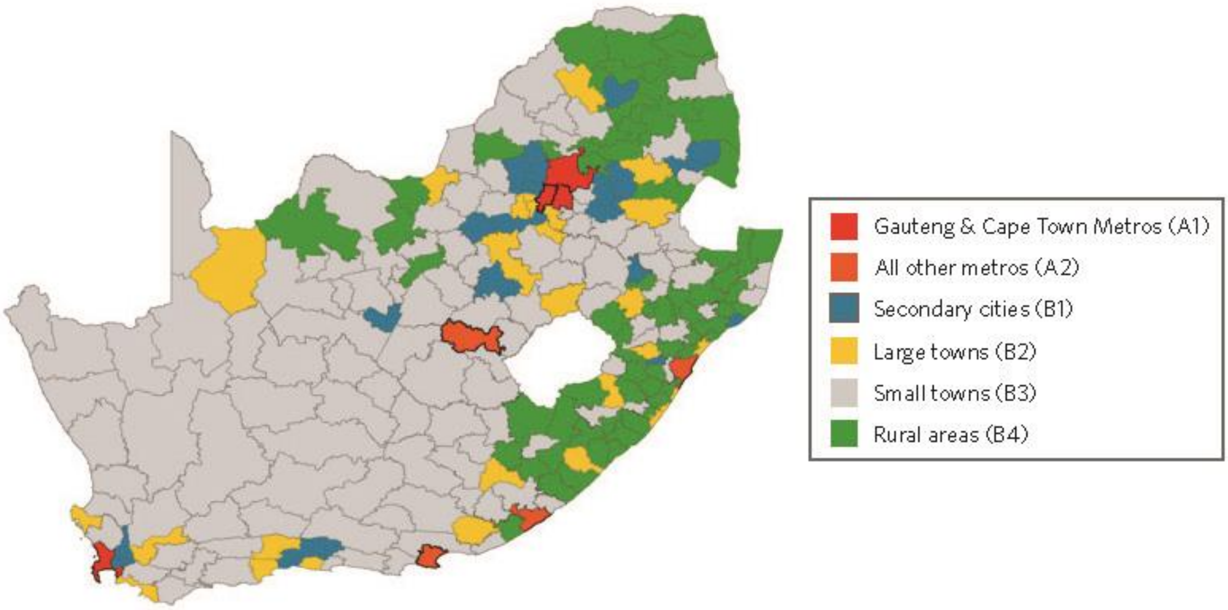
[12] Peri-urban households refer to areas adjacent to urban areas.



Source: Reproduced from Arndt et al. (2018, p. 5)

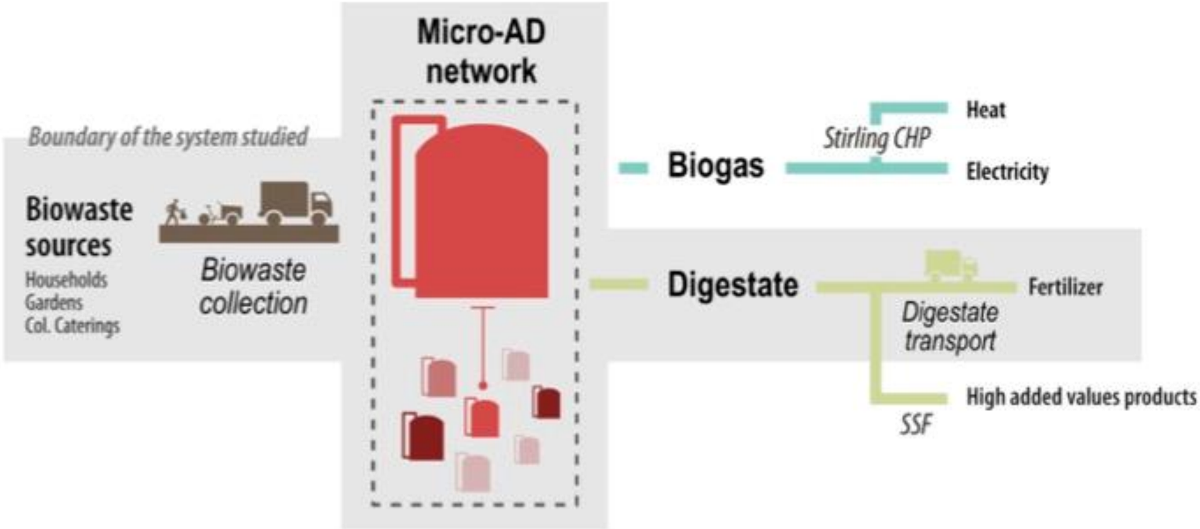
Note: Red (green) indicates higher (lower) density or urban shares.

Figure 5. Classification of Municipalities into Urban and Rural Areas



Source: Reproduced from Arendt et al. (2018, p. 7)

Figure 6. Simplified scheme of the decentralized biowaste treatment network



Source: Reproduced from Thiriet et al. (2020, p. 2)

The market segment for micro-scale digesters may be further divided between rural and urban electrified and non-electrified households. The various energy sources' needs assessment, benefits, and costs would be assessed differently between the four groups. For example, a key argument underpinning subsidised biogas programmes for the rural households' market segment pertains to the associated non-financial benefits of displacing traditional carbon-based fuels and solid biomass like firewood and access to energy for households not connected to the power grid. However, significant strides have been made in the electrification of South African households.

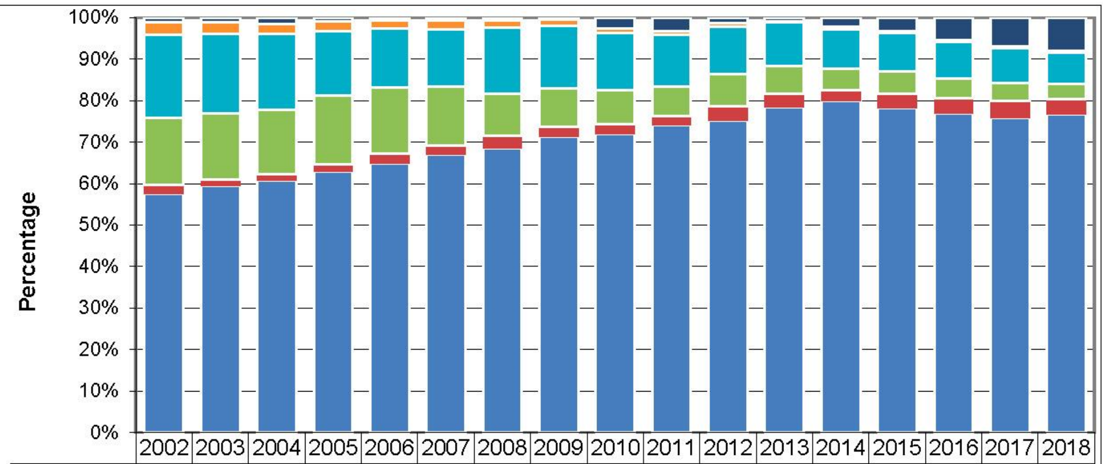
In the General Household Survey, 2018, electricity supplied from the grid provided the bulk of energy for lighting, cooking and heating water while making the largest contribution to heating space (Table 4). In the period 2002 - 2018, the use of electricity for cooking increased from 57% to 76% of households, replacing energy sources like wood (20% to 7.7%), coal (3% to 0.4%), and paraffin (16% to 3.6%) (Figure 5). The option for clean energy for cooking as a substitute for biomass or traditional fossil fuels may, therefore, have greater purchase in rural provinces such as Limpopo and Mpumalanga, where a significant portion of households still use wood for cooking - 31.6% and 16.2%, respectively (Figure 6).

Table 12. All sources of energy used for cooking, lighting and heating, 2018

	Lighting	Cooking	Heating water	Heating space
Electricity from mains	87,2	81,3	82,5	38,0
Other source of electricity	8,2	7,9	7,9	4,2
Gas	0,8	6,9	3,2	3,4
Paraffin	3,4	7,7	7,1	7,3
Wood	N/A	14,4	12,9	13,0
Coal	N/A	1,2	1,0	1,6
Candles	16,3	N/A	N/A	N/A
Animal dung	N/A	0,8	0,8	0,7
Solar energy	0,7	0,1	0,5	0,1
Other	0,1	0,0	0,0	0,4
None	0,0	0,1	0,2	21,3

Source: Reproduced from StatsSA (2018, p. 39)

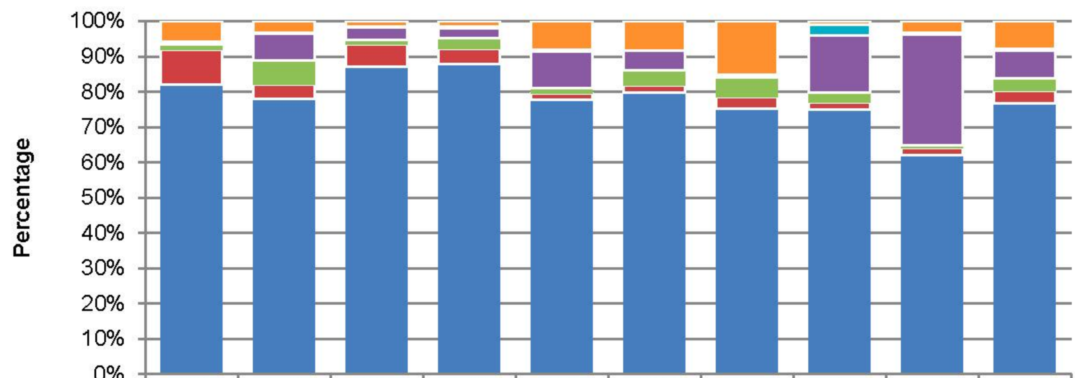
Figure 7. Percentage distribution of main sources of energy used for cooking by year, 2002–2018



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Other	1,2	1,1	1,4	0,8	0,6	0,6	0,6	0,5	2,5	3,1	1,3	0,8	2,1	3,3	5,4	6,9	7,9
Coal	3,0	2,7	2,4	2,4	2,1	2,2	1,8	1,3	1,2	0,9	0,8	0,4	0,6	0,5	0,5	0,4	0,4
Wood	20,	19,	18,	15,	14,	13,	15,	15,	13,	12,	11,	10,	9,7	9,1	8,8	8,4	7,7
Paraffin	16,	15,	15,	16,	15,	14,	10,	9,4	8,4	7,0	7,8	6,8	5,0	5,4	4,7	4,2	3,6
Gas	2,2	1,6	1,7	1,8	2,2	2,2	3,0	2,2	2,2	2,1	3,3	3,2	2,7	3,5	3,8	4,2	3,6
Electricity	57,	59,	60,	62,	64,	67,	68,	71,	72,	74,	75,	78,	79,	78,	76,	75,	76,

Source: Reproduced from StatsSA (2018, p. 38)

Figure 8. Percentage distribution of main sources of energy used for cooking by year, 2018



	WC	EC	NC	FS	KZN	NW	GP	MP	LP	RSA
Other	5,8	3,3	1,6	1,5	8,2	8,2	15,0	1,0	3,2	7,9
Coal	0,0	0,1	0,1	0,4	0,3	0,0	0,2	3,0	0,5	0,4
Wood	0,8	7,8	3,5	2,8	10,4	5,7	0,6	16,2	31,6	7,7
Paraffin	1,3	6,7	1,4	3,1	1,7	4,4	5,8	2,7	0,6	3,6
Gas	9,9	4,2	6,3	4,3	1,7	2,0	3,1	2,1	2,0	3,6
Electricity	82,2	77,9	87,1	87,9	77,8	79,8	75,4	75,0	62,2	76,8

Source: Reproduced from StatsSA (2018, p. 38)

COMMUNAL SPACES AND INSTITUTIONS

Community-centred institutions and communal spaces also offer promising market opportunities for micro-scale digesters. SANEDI has installed over 80 units at schools, colleges, universities, community development facilities and Early Childhood Development Centres. In 2019, there were just under 25 000 ordinary public and independent schools (Department of Basic Education (DBE) 2020) (Appendix B). Other communal spaces could include public, private and community gardens, urban farms, hospitals and clinics, nursing and care homes, and community development facilities (Table 5). Like households, these spaces and institutions could also connect to micro-digester networks (Figure 4)

As with households, electrified and non-electrified communal spaces and social institutions would likely have different needs while assessing the benefits and costs of the various energy sources differently. However, micro-digesters could reduce the costs of waste management and electricity. The size of the institution or communal space, and the amount and type of feedstock available, would also impact whether micro-scale or larger small-scale digesters would be more appropriate to treat waste at source.

Table 13. Market segment sizes for communal spaces and institutions

Category	Number	Reference(s)
Schools (ordinary public and independent)	24 998	DBE (2020) (Appendix B)
Post-school education and training institutions	487	DHET (2018)
Early childhood development centres	696	CECD (2020)
Hospitals	544	Dell and Kahn (2017)
Primary health care facilities (including clinics, tertiary and district hospitals)	3477	Padarath and Barron (2017)
Urban community gardens	Unknown*	

*Academic literature has focussed on specific districts or regions. A cursory review suggests several hundred may be in operation around the country.

HOSPITALITY SECTOR

A third target market of potential customers can be located in the hospitality sector. Private sector companies in South Africa have installed micro-scale digesters at game-, wine- and bush farms around the country, of which there are several thousand around the country (Table 6). As this is proprietary information, the number of establishments fitted with digesters and the extent to which this segment has proved profitable for the private sector is unknown.

The food and beverages sector has historically been active in adopting bioenergy initiatives utilising waste. Western Cape-based company Envirodiesel collects waste cooking oil from leading provincial food establishment chains Spur Steak Ranches, Panarottis Pizza Pasta, and John Dory's Fish & Grill to convert into biodiesel (Esterhuizen 2012). In the United Kingdom, half of the biodiesel powering MacDonald's transport fleet is sourced from its waste cooking oil (Mcdonalds.com 2021).

These examples suggest reasonable grounds for incorporating businesses into innovative renewable energy initiatives – if feasibility can be established.

Restaurants and canteens may have viable sources of feedstocks for biogas production from micro-scale digesters (Thiriet et al. 2020) as part of urban micro-digester networks (Figure 4). Pre-COVID, the food and beverages sector made a significant contribution to GDP and employment, with the formal sector reporting a total income of R72.3 billion in 2018 (StatsSA 2020b). 56.9% of industry employment and 50.8% of revenue was created by small, medium and micro enterprises – suggesting several thousand small businesses who generate organic waste. There may also be opportunities in the extensive network of state-owned tourism and hospitality facilities. For example, the South African National Parks serviced approximately 6.5 million guests across 4 million hectares of land under conservation for the year ended March 2019.

Table 14. Market segment sizes for the hospitality sector

Category	Number	Reference(s)
Game farms	11 500	Chiyangwa (2018)
Wine farms and wineries	3 311	SAWIS (2019)
Restaurants and food outlets	7000+	Planting (2020)

MARKET DEVELOPMENT

Several methodologies are available to assess the prospects for a product market. For this report, we consider the development of a sustainable market-based industry contingent upon the adoption of biogas as a source of bioenergy, alongside the distribution of the technologies to facilitate its production. Given the objective of providing insight into the industry's potential, the method selected analyses the factors influencing or known to likely influence biogas' wider adoption. Nevzorova and Kutcherov (2019) undertook a meta-review and analysis of the existing literature on barriers to biogas uptake in developing and developed countries. Through thematic analysis, they developed six categories (i) technical, (ii) economic, (iii) market, (iv) institutional, (v) socio-cultural, and (vi) environmental grouping factors likely to constrain or present bottlenecks. Adapting their approach, we analysed primary and secondary data to identify key factors in the South African micro-scale digester market. The primary data was collected in March 2021, and respondents included both households and schools. These findings are summarised in a tabular format below, along with an indication of their anticipated impact on market demand and supply.

TECHNICAL FACTORS

Technical factors are concerned with the production process, referring to inputs, the technology used, logistics, digester operation and maintenance (Table 7), and Nevzorova and Kutcherov (2019) find that these are raised with the most frequency in developing countries. A preliminary review of recent fieldwork data suggests that feedstock availability can impact digester performance. Responses reference no cow dung in the rainy season, lack of feedstock resulting in inconsistent feeding, low usage due to lack of feedstock. Literature suggests that construction issues frequently occur for built digesters (DIFD 2011; Mukumba et al. 2016; Mutungwazi et al. 2018). Many respondents had hired technicians feeding the digesters, which may be a critical success factor, and all respondents appeared to have easy access to water. A 2018 closeout report for the Mpfuneko Rural Domestic Biogas Project revealed it took four years to build 55 brick and mortar fixed dome digesters, where delays were attributed to poor workmanship and drought, amongst others. Most respondents reported no maintenance since the unit was constructed.

Table 15. Key technical factors impacting the domestic market

Technical Factor		Findings	Market impact
Feedstock availability	-Sufficient feedstock must be available to produce biogas.	-Certain market segments may not be able to maintain the digester throughout the year. -Seasonal feedstocks may reduce biogas production rates.	↓ Demand-side
Water availability	-An adequate supply of water is required for the anaerobic digestion process.	-South Africa is a water-scarce country, and potential customers would need to consider the viability of installing a digester if the water supply is not secure. -The cost of water needs to be taken into account when assessing economic feasibility.	↓ Demand-side
Construction and installation	-Skilled staff are required to construct or install prefabricated digesters. -Availability of materials and resources.	- Construction issues are frequent for built digesters. - Training programmes have not always been successful. -Material for construction is locally available. -Prefabrication provides greater standardisation and quality assurance.	↓ Supply-side
Repairs and maintenance	-Technical failure due to poor construction or manufacturing. -Lack of attention to maintenance. -Lagging service management.	-Digester longevity needs to be considered. -Digesters are not always maintained. -Poor performance due to maintenance issues negatively impact perceptions.	↓ Demand-side

ECONOMIC AND FINANCIAL FACTORS

The high up-front cost of installing a digester is considered one of the primary factors inhibiting this technology's deployment (Nevzorova and Kutcherov 2019). Respondents to the survey reported a wide range of savings due to switching to biogas, from as little as R30 to as much as R4000, with schools appearing to generate the most savings. Savings were likely linked to operational factors, and none were reported where the digester was not operating. Almost all respondents to the recent fieldwork survey did not realise the economic value of the fertiliser. Units were funded by the government and non-governmental organisations (NGOs), with no external finance access.

Table 16. Key economic and financial factors impacting the domestic market

Economic/Financial Factor		Findings	Market impact
Investment Cost	-Cost of purchasing a micro-scale digester in South Africa.	-Compared to other energy sources, the initial investment required for a micro-scale anaerobic digester is significant. -Market segments that would most benefit are least likely to afford the initial cost. -Insufficient cash generation to offset digester investment cost.	↓ Demand-side
Availability of subsidies	-Governments and/or development agencies may subsidise initial investment costs.	-Subsidies have been central to existing pilot projects. -Subsidies may be critical for particular market segments.	↑ Demand-side
External finance	-Availability of bank or other finance.	-Not all market segments will have the income to qualify for external finance.	↓ Demand-side
Exchange rates	-Exchange rate impact on imported materials, digesters, parts	-Imported prefabricated units will be subject to price fluctuations.	↓ Demand-side
Fertiliser (by-product)	-The economic value of fertiliser by-products	-Fertiliser is a valuable by-product of the anaerobic digester process. -The economic value of fertiliser is often no realised.	↑ Demand-side

ENERGY MARKET FACTORS

Energy market factors are concerned with substitute products that could compete with biogas produced from micro-scale digesters to meet new or existing energy requirements. The cost and accessibility of competitive energy products will be critical. Reported savings suggest that the biogas was more competitive for firewood for some respondents. Savings from not purchasing firewood exceeded those obtained when switching from electricity and gas.

Table 17. Key energy market factors impacting the domestic market

Energy Market Factor		Findings	Market Impact
Fossil fuel prices	-Oil and gas prices on the international market.	-Fossil fuel prices influence the feasibility of renewable energy projects. -Low fossil fuel prices are likely to continue until externalities are incorporated into market prices.	↓ Demand-side
Electricity costs	-Cost of electricity supplied from the grid.	-Electricity costs are comparatively low when consumers are connected to the grid.	↓ Demand-side
Biomass cost	-Cost of traditional solid biomass, e.g. firewood.	-Although its use is on the decline, the comparatively low cost of traditional solid biomass may be significant for some households.	↑ Demand-side

INSTITUTIONAL FACTORS

Institutional factors are concerned with governance, government support, legislation and regulation. Micro-scale digesters have typically relied on significant support from government and development agencies, particularly for rural and economically deprived communities. While limited biogas awareness campaigns have been cited as an impediment to technology deployment, the South African government has instituted several policy initiatives to support the industry's development (see UJ-PEETS 2020). In the recent fieldwork conducted for SANEDI, all digesters were funded by the government or NGOs.

SOCIO-CULTURAL FACTORS

Socio-cultural factors refer to cultural and social factors that can impact technology adoption, including values, ethics, cultural preferences, and educational aspects. Research suggests that consumer interest and public participation are essential for building awareness and a positive perception of biogas in a community (DIFD 2011; UJ-PEETS 2020). Several survey respondents reported positive feedback from community members. Several responses referred to community members' surprise and excitement at generating energy from gas while expressing interest in acquiring a digester. In instances where the digester was not operational, community members were cautious, waiting to see if the digester would work. The success of pilot programmes may be critical for widespread adoption. Most respondents reported very high satisfaction with their digester unit.

ENVIRONMENTAL FACTORS

Research suggests several environmental factors may inhibit technology uptake. These include odour and noise, pollution, and water availability in water-scarce areas (Table 12). While drought hindered the roll-out of the Mpfuneko Rural Domestic Biogas Project, most respondents have easy access to water, and water resources were not raised as problematic. Only one respondent reported smell complaints.

Table 18. Key institutional factors impacting the domestic market

Institutional Factor		Findings	Market Impact
Legislation and regulation	-Legislation and regulation governing manufacturing, installation and operation of micro-scale digesters.	-Registration with NERSA for micro-scale digester owners. Limited compliance. -Biogas currently covered indirectly under several acts. -The regulatory environment does not appear to hinder demand materially.	↓ Supply-side
Institutional support	-Government and government agency participation -University support	-There have been several pilot programmes underwritten by government funding to develop and test micro-scale digester technology in different markets. E.g. SANEDI, Working for Energy programme -Governments are critical role players in developing markets for bioenergy. -Research and development support has been made available for several universities in South Africa to explore and develop the technology.	↑ Demand-side ↑ Supply-side
Policy support	-Policy initiatives and instruments for the biofuel industry, e.g. tax credits, subsidies	- Policymakers and advisers have called for specific biofuel policies and standards to support industry development.	↓ Demand-side ↓ Supply-side

Table 19. Key socio-cultural factors impacting the domestic market

Socio-cultural Factor		Findings	Market Impact
Consumer interest and public participation	-Familiarity with technology, bioenergy, sustainable energy systems Cultural factors influence technology adoption	-Users have to adapt to new processes and routines. -Operational challenges have been reported leading to disuse. -Community members have been intrigued and surprised by the technology. -Positive community engagements with pilot programmes may well be critical for broader adoption.	↑ Demand-side

Table 20. Key environmental factors impacting the domestic market

Environmental Factor		**Findings**	**Market Impact**
Odour and noise	-Odour and noise complaints	-Odour complaints have been raised in prior surveys and interviews, but only one complaint was submitted in the recent survey.	⇣ Demand-side
Water resources	Water availability	Water is a critical resource, particularly in water-scarce regions.	⇣ Demand-side
Pollution	Increased pollution	-Leaking digesters can contaminate groundwater or increase GHG emissions sources if poorly maintained. -Fertiliser by-product can disseminate harmful pathogens through handling or via crops.	⇣ Demand-side

MARKET POTENTIAL

The potential market size for a product is generally calculated as the market's size multiplied by an estimated penetration rate. Considering the very low penetration rate in South Africa, in conjunction with our estimated penetration rates internationally, scenarios of 0.05%, 0.1%, 0.25%, 1%, and 10% were considered for each market segment (Table 13). Households in Limpopo, Mpumalanga and Kwa-Zulu Natal were also listed separately, as provinces still heavily rely on firewood for cooking and heating.

Table 21. Market scenarios for South Africa based on estimated segment sizes*

Category	**100%**	**0.05%**	**0.1%**	**0.25%**	**1%**	**10%**
Households	16 671 000	8 333	16 671	41 677	166 710	1 667 100
Households – Limpopo, Mpumalanga	5 773 000	2 886	5 773	14 432	57 730	577 300
Schools (ordinary public and independent)	24 998	12	24	62	249	2 499
Post-school education and training institutions	487	-	-	1	4	48
Early childhood development centres	696	-	-	1	6	69
Hospitals	544	-	-	1	5	54
Primary health care facilities (including clinics, tertiary and district hospitals)	3477		3	8	34	347
Urban community gardens	100+	-	-	-	1+	10+

Game farms	11 500	5	11	28	115	1 150
Wine farms and wineries	3 311	1	3	8	33	331
Restaurants and food outlets	7000+	3+	7+	17+	70+	700+

*Unit projections are rounded down to the nearest whole number. Segment size estimations are drawn from Section 4, Market Segments. A conservative baseline estimate of urban community gardens is provided.

The potential market for households may well run into tens of thousands when considered relative to other developing countries. Significant social, economic and environmental benefits for rural households will likely accrue, particularly to those who still rely on traditional solid biomass fuels. However, this market segment is unlikely to support a sustainable market-based micro-scale digester industry. The high investment costs and the lack of cash flow to service debt suggest that this segment will likely require ongoing government or developmental agency financial support to switch to digester-produced biogas as a clean energy source. Given the many socio-economic benefits, such subsidisation should be carefully considered.

However, most South Africans reside in urban areas and are governed by urban municipalities. A sustainable industry for urban and peri-urban households may be more promising in the long term. Prefabricated, moulded plastic digesters which utilise smaller quantities of organic waste will probably be more suitable. Decentralisation of waste management at the source, coupled with increased cost, could also support the widespread deployment of micro-scale digester networks in these areas. Developing such networks is still an emerging area in renewable energy-related urban development and planning.

Theoretically, several thousand communal spaces and institutions could adopt micro-scale digester technology, but penetration levels will have to exceed 10%, representing a significant roll-out. However, survey respondents' feedback is promising, with schools indicating savings and associated cash flow benefits from switching to biogas. In rural areas and economically deprived areas, cost and operation are likely to be primary factors. In urban and peri-urban areas, socio-cultural factors are likely to be significant. However, increases in either the cost of waste management or substitute energy products may provide the necessary cost-based incentives to adopt the technology. Different types of communal spaces and institutions would need to be analysed independently to assess their market viability, including digester technology's appropriate type and size.

The hospitality industry may offer the most commercially sustainable market but will likely be commercially viable if market penetration rates significantly exceed 10%. Thousands of small farms, many of which operate as tourist destinations, will produce the necessary feedstocks. As businesses, the appropriate processes can be incorporated into business operations to ensure digesters are run optimally. Cost concerns will, however, be key. Private sector companies are already servicing this market, although market penetration is unclear, given the proprietary nature of this type of information. In the long term, restaurants and canteens in urban and peri-urban areas could also participate in micro-scale digester networks.

CONCLUSIONS AND RECOMMENDATIONS

Several market segments have been identified that could support the development of a sustainable market-based industry for micro-scale anaerobic biogas digesters. Much of the international and international research has focussed on rural households to support efforts to improve socio-economic conditions by providing better access and cleaner energy. Conversely, this market is least equipped to adopt the technology through market-based mechanisms due to financial constraints, given the high initial investment required to install a micro-scale digester.

Given the likely varying needs and preferences of the identified market segments, a stratified approach to refining the market potential and estimating penetration rates should be considered. There is insufficient information available in the public domain to decisively conclude market penetration in each proposed segment over the next five years. The appropriate technology for each market segment should be definitively established, taking factors such as cost, size, feedstock availability, and operational requirements into account. Detailed surveys should be conducted for both existing consumers and potential consumers in each market segment to provide the necessary information to establish needs and preferences, market size and identify any challenges and obstacles.

Given the myriad of factors that influence adoption, it would also be useful to understand these factors independently for each of these market segments in the South African context. Pilot projects for preferred technologies should then be considered to provide the necessary data, in addition to those programmes currently underway. Targeted interventions could then be introduced to address market demand and supply factors to improve market penetration rates to economically viable levels. Recent feedback from schools and households for built digesters is promising, but these units have been funded. An improved understanding of the discrepancies between cost savings should be undertaken to establish the break-even cost for each type of digester, which would provide a floor for the required cost-savings to justify a particular unit financially. Appropriate strategies to overcome demand-side bottlenecks and challenges, as represented by the key factors impacting technology adoption, can be devised for each segment when sufficient information is available. For urban and peri-urban households, communal spaces and institutions, and hospitality establishments, the potential of developing micro-scale digester networks as part of urban waste management planning should be explored. As the cumulative threshold for GHG emission reductions draws nearer, the costs of managing bio-waste and the penalties for exceeding emission targets may make such networks critical in the future.

The high cost of micro-scale digesters in South Africa relative to other countries should also be investigated to determine if cost reductions could be achieved and what economies of scale would be necessary to do so.

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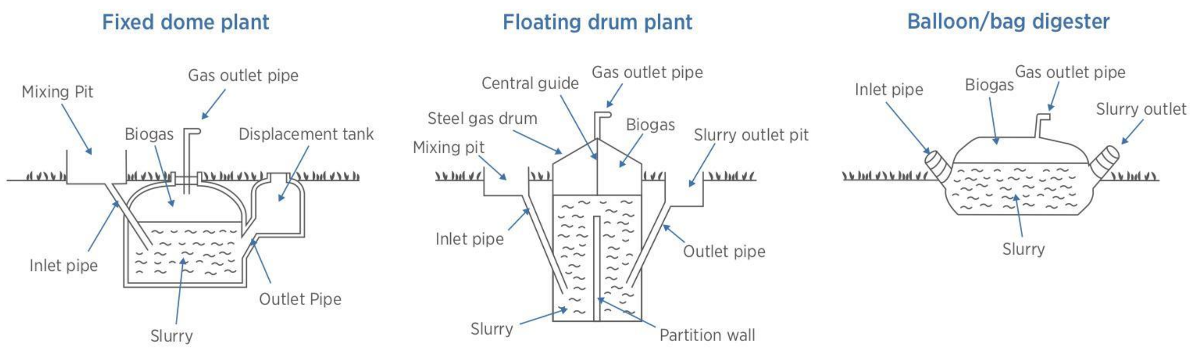
APPENDIXES

APPENDIX A - MICRO-SCALE ANAEROBIC BIOGAS DIGESTER DESIGNS

Figure 1. Illustrations of the three main small-scale biogas digesters: fixed dome plant, floating drum plant and balloon/bag digester



Source: Reproduced from IRENA (1017, p.10)

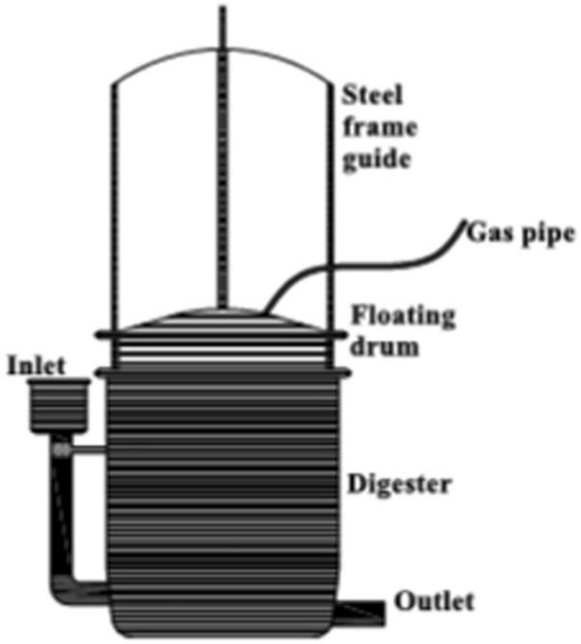
Figure 2. The AGET 2.5 m3 portable biogas digester

Source: Reproduced from Mutungwazi et al. (2018, p. 176)

Figure 3. The AGET Underground 10 m3 digester and biobag

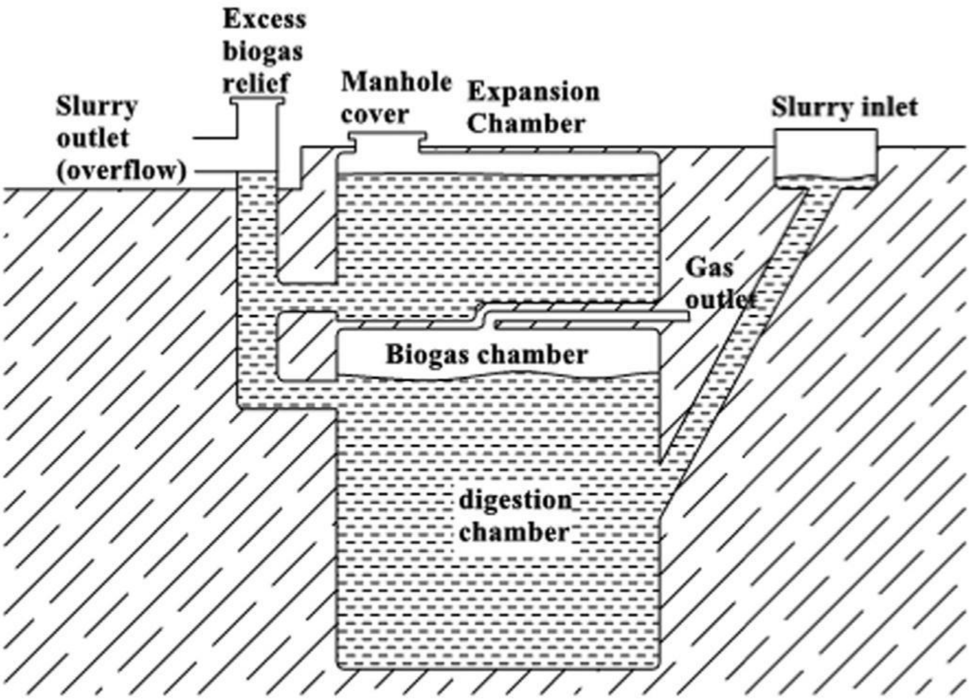
Source: Reproduced from Mutungwazi et al. (2018, p. 174)

Figure 4. Illustration of the EZ-digester



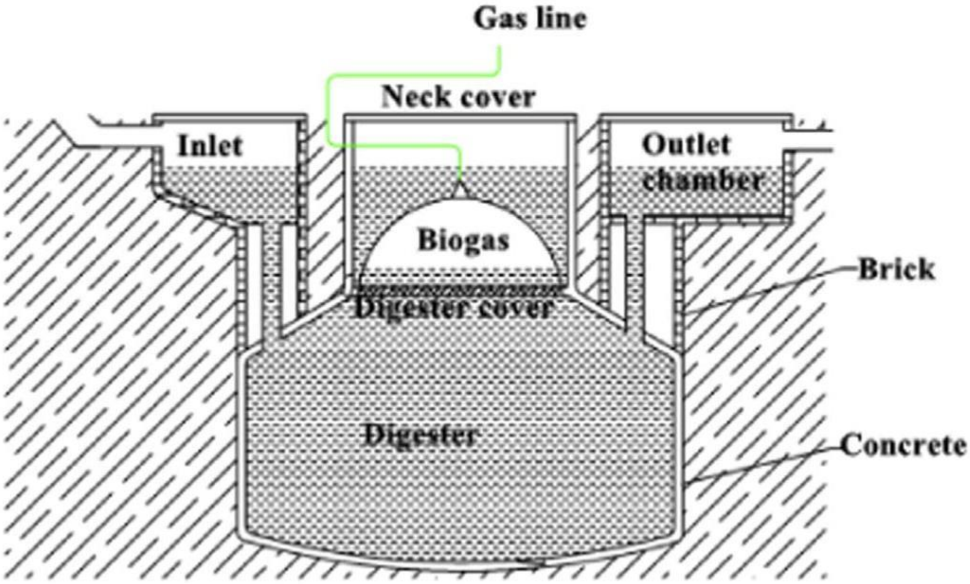
Source: Reproduced from Mutungwazi et al. (2018, p. 176)

Figure 5. Illustration of the Little Green Monster digester



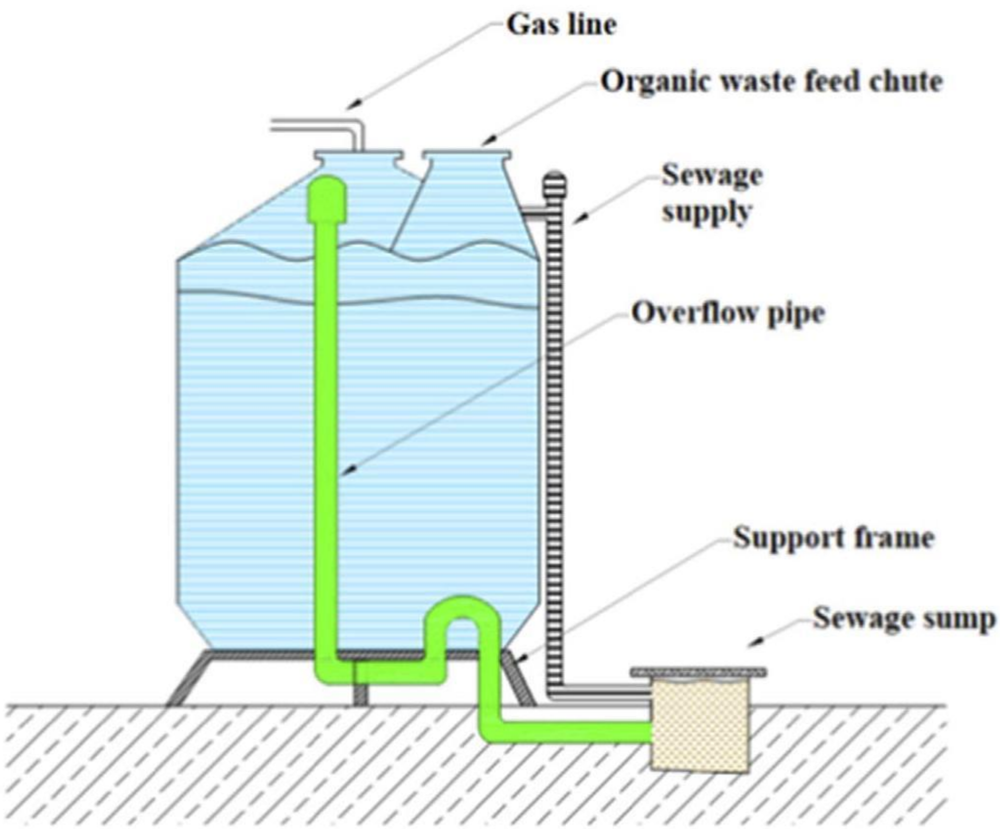
Source: Reproduced from Mutungwazi et al. (2018, p. 177)

Figure 6. Illustration of the in situ concrete micro-scale digester



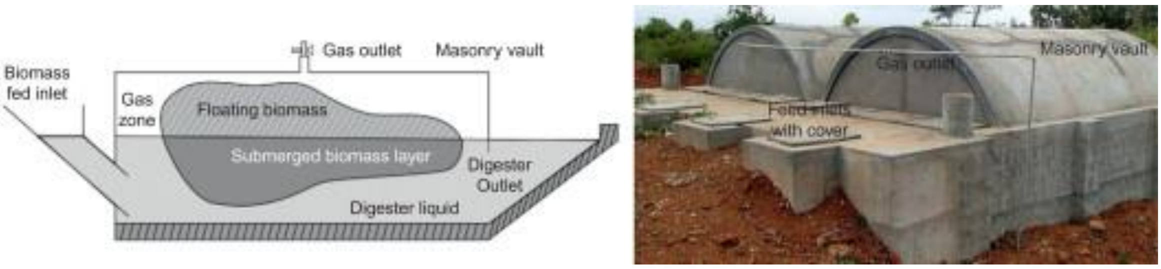
Source: Reproduced from Mutungwazi et al. (2018, p. 177)

Figure 7. Illustration of the AGAMA fixed dome digester



Source: Reproduced from Mutungwazi et al. (2018, p. 177)

Figure 8. Illustration of a plug-flow digester



Source: Reproduced from Teng et al. (2014)

APPENDIX B - MARKET SEGMENT DATA

Table 1. Population per province, 2002–2018

	Total population (Thousands)									
	WC	EC	NC	FS	KZN	NW	GP	MP	LP	RSA
2002	4 756	6 515	1 030	2 645	9 660	3 054	9 764	3 478	5 019	45 921
2003	4 858	6 505	1 040	2 652	9 718	3 097	10 010	3 530	5 050	46 461
2004	4 960	6 498	1 050	2 661	9 783	3 141	10 258	3 586	5 085	47 021
2005	5 063	6 493	1 060	2 670	9 853	3 186	10 511	3 643	5 123	47 602
2006	5 168	6 489	1 071	2 680	9 928	3 232	10 772	3 701	5 165	48 205
2007	5 276	6 484	1 082	2 691	10 005	3 281	11 044	3 760	5 207	48 830
2008	5 388	6 480	1 093	2 704	10 087	3 330	11 325	3 820	5 252	49 479
2009	5 502	6 478	1 105	2 717	10 175	3 382	11 612	3 883	5 299	50 152
2010	5 618	6 477	1 117	2 732	10 268	3 434	11 910	3 947	5 349	50 850
2011	5 738	6 476	1 130	2 748	10 365	3 488	12 219	4 012	5 400	51 574
2012	5 860	6 476	1 143	2 764	10 468	3 545	12 539	4 078	5 453	52 325
2013	5 985	6 477	1 156	2 782	10 576	3 603	12 868	4 147	5 511	53 104
2014	6 112	6 481	1 170	2 802	10 691	3 663	13 203	4 218	5 573	53 912
2015	6 242	6 486	1 184	2 822	10 812	3 726	13 549	4 291	5 638	54 750
2016	6 374	6 492	1 199	2 844	10 941	3 790	13 906	4 367	5 707	55 620
2017	6 510	6 499	1 214	2 867	11 075	3 856	14 278	4 444	5 779	56 522
2018	6 650	6 508	1 230	2 891	11 215	3 925	14 661	4 523	5 854	57 458

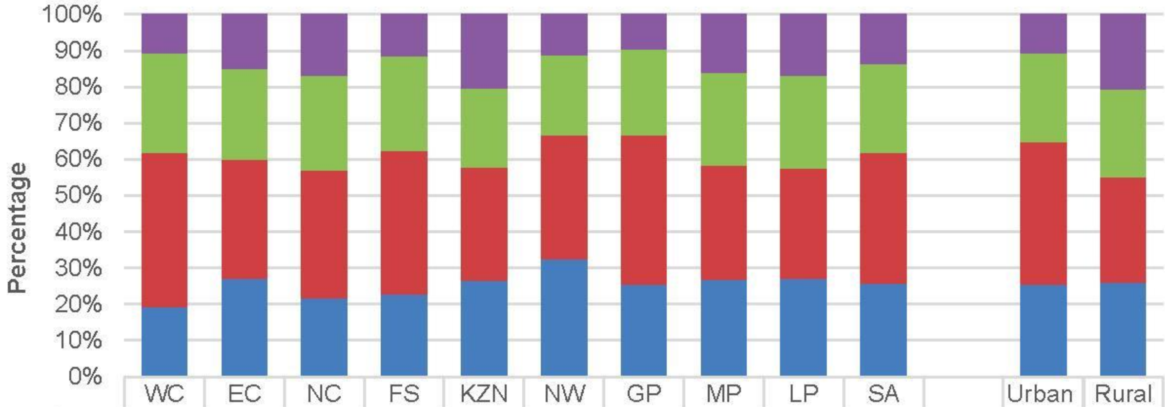
Source: Reproduced from StatsSA (2018, p. 2)

Table 2. Population per province, 2002–2018

	Total population (Thousands)									
	WC	EC	NC	FS	KZN	NW	GP	MP	LP	RSA
2002	1 217	1 506	247	679	2 070	767	2 785	801	1 121	11 194
2003	1 251	1 518	252	692	2 105	789	2 882	827	1 144	11 459
2004	1 287	1 526	257	703	2 137	812	2 982	851	1 164	11 718
2005	1 323	1 530	261	715	2 168	834	3 088	876	1 181	11 977
2006	1 360	1 532	266	726	2 198	858	3 202	902	1 199	12 243
2007	1 396	1 541	272	738	2 240	881	3 305	929	1 222	12 522
2008	1 432	1 551	277	751	2 284	906	3 416	956	1 247	12 819
2009	1 469	1 561	282	763	2 331	930	3 537	984	1 272	13 128
2010	1 507	1 571	287	775	2 382	956	3 668	1 013	1 298	13 456
2011	1 547	1 580	293	787	2 434	982	3 807	1 043	1 324	13 797
2012	1 585	1 596	299	801	2 495	1 008	3 938	1 074	1 357	14 152
2013	1 626	1 611	305	815	2 556	1 037	4 075	1 105	1 390	14 521
2014	1 670	1 624	311	830	2 619	1 067	4 220	1 138	1 424	14 904
2015	1 718	1 636	318	845	2 683	1 099	4 377	1 172	1 459	15 307
2016	1 771	1 648	325	862	2 752	1 135	4 546	1 208	1 495	15 744
2017	1 823	1 667	333	882	2 827	1 172	4 709	1 248	1 537	16 199
2018	1 877	1 685	342	901	2 905	1 210	4 884	1 289	1 579	16 671

Source: Reproduced from StatsSA (2018, p. 3)

Table 3. Percentage of households of different sizes by province and rural/urban status, 2018



	WC	EC	NC	FS	KZN	NW	GP	MP	LP	SA		Urban	Rural
6+	10,6	14,9	16,8	11,6	20,3	11,3	9,4	16,2	16,8	13,6		10,6	20,6
4-5	27,6	25,1	26,1	26,1	21,9	21,9	23,9	25,5	25,6	24,4		24,5	24,3
2-3	42,6	33,0	35,4	39,6	31,3	34,3	41,1	31,4	30,5	36,3		39,5	29,0
1	19,2	27,0	21,8	22,8	26,4	32,6	25,5	26,9	27,1	25,7		25,5	26,1

Source: Reproduced from StatsSA (2018, p. 5)

Table 3. Summary Statistics for Urban-Rural Regions, 2016

	South Africa	Gauteng & Cape Town (A1)	Other metros (A2)	Secondary Cities (B1)	Large Towns (B2)	Small Towns (B3)	Rural Areas (B4)
Population (mil.)	55.6	16.0	6.3	7.9	4.5	7.5	13.4
Share (%)	100	28.7	11.4	14.2	8.0	13.5	24.2
Urban pop. share, 2011 (%)	0.91	98.1	87.6	71.9	65.7	58.5	7.9
Pop. density (people/sq. km)	4.71	1,155	466	137	43	9	52
Total GDP (R bil.)	2,733	1,118	408	485	201	292	229
Share (%)	100	40.9	14.9	17.7	7.4	10.7	8.4

Source: Extracted from Arndt et al. (2018, p. 8)

Table 5. Number of ordinary schools, by province, in 2019.

Province	**Schools**
Eastern Cape	5 430
Free State	1 156
Gauteng	2 813
KwaZulu-Natal	6 036
Limpopo	3 931
Mpumalanga	1 795
Northern Cape	583
North West	1 536
Western Cape	1 718
South Africa	24 998

Source: Reproduced from Department of Basic Education (2020, p. 1)

Annex 4: Political economy analysis

1. Description of the Political Economy Analysis

The Political Economy Analysis (PEA) is an analysing tool for exploring the distribution of power and resources in a system or sector. PEA contributes to understanding the political and economic forces at play, where power lies and why, the type of interests of various actors, and identifies the beneficiaries or losers. The concept investigates the governance as well as influences on the decision-making process.

The purpose of this PEA is to provide comprehension of the political and economic forces that impact the micro biogas digester sector. This analysis reveals power relationships between actors, vested interests and the nature of resistance to change. The report is based on a literature review of reports and academic papers written on the challenges and opportunities of micro digesters for clean energy access from South Africa and around the world. The literature review was conducted using Science Direct and Scopus databases. A keyword search was done using the following combinations: micro digesters + South Africa; biogas + South Africa; Biogas + energy access; biogas + developing countries; biogas + challenges; biogas + barriers.

The literature review results found that articles on the political economy of micro biogas digester are scarce, and there are few analyses on the technological, policy, economic and environmental aspects from developed and developing countries. Four studies in particular, however, stood out:

1. Hamid and Blanchard (2018) conducted a feasibility analysis for the potentiality of biogas to provide clean energy in rural areas of Kenya. They assessed the suitable technology type and business model and analysed rural areas' economic and social conditions. The results showed a high technical potential for biogas in western and central Kenya due to the availability of land and cattle manure, although water availability is challenging. The inflatable plug-flow digester, with its low cost and ease of operation, was found to be most suitable and met the social and economic conditions of rural areas. The study suggested that community biogas entrepreneurship projects are solutions to mitigate biogas technology barriers. The study encouraged the development of the technology in order to meet the goals of the Kenyan Biogas Development Programme. It also demonstrated that rural areas have the potential to use biogas for reducing expenditures, meeting domestic needs and contributing to social development.
2. Nevzorova and Kutcherov (2019) reviewed the barriers which prevent the uptake of biogas energy in developed and developing countries. They analysed technical, economic, market, institutional, socio-cultural, and environmental barriers. Technical barriers, among others, are infrastructural challenges regarding the availability of resources and plant size, technical failures and problems, lack of specialised staff, dependence on imported material and insufficient follow-up services. The economic barriers are comprised of the high cost of biogas production, transportation, clean up and upgrading. Institutional barriers are related to the lack of political support and legislation, uncertain policy landscape, lack of private sector participation, weak coordination between public and private sectors, high bureaucracy with complex administrative and legal procedures. The socio-cultural barriers involve religious and cultural outlooks, including stigmatisation, lack of public participation and interest. Environmental barriers point to odour and noise complaints, lack of adequate water and availability of feedstock resources. The study concluded that the involvement of

multiple stakeholders is important and widespread information on the benefits of biogas energy to the public.

3. Raha et al. (2014) analysed the Indian programme for the implementation of decentralised biogas and assessed the outcomes. They revealed that the programme offers improved energy services to most households and that users lack knowledge and information on biogas technology. The authors argued that various factors contribute to accelerating the deployment of biogas technologies. For instance, community empowerment, awareness, training and education, particularly of women, play a significant role in the deployment of the technology. Women mostly feed, operate and maintain biogas systems in addition to their capacity of influence within communities and households. Hence, their empowerment is beneficial to the programme, and biogas implementation cannot be gender blind. The study recommended an adaptation of the programme policy to consider gender, augment competition between contractors and facilitate community-based business models.
4. Horschig et al. (2020) are one of the very few studies which analyse stakeholders' linkages in the biogas sector. The authors used the influence/interest matrix approach and examined the stakeholders' perception of the sustainability of biogas in Germany. They denoted that key sector players are farmers, policymakers, environmental Non-Governmental Organisations (NGOs) and biogas associations. Surveyed stakeholders revealed their agreement on regulating sustainability at the national level in the biogas sector. There are disagreements over which sustainability standards and how to implement them. The lack of economic stimulation and market incentives constitute a barrier to this. Incentives to develop a bioeconomy are low, although biogas plants have the potential to play a key role in the future of bioeconomy. The study results demonstrated that stakeholders are expecting clear and transparent rules from the government to guide sustainability.

2. A PEA of the micro-biodigester sector in South Africa

The PEA framework used in this report follows the Department for International Development (DFID)'s conceptual framework for PEA. This framework refers to PEA as 'the interaction of political and economic processes in a society: the distribution of power and wealth between different groups and individuals, and the processes that create, sustain and transform these relationships over time' (Collinson, 2003, p. 3). DFID's PEA includes a Drivers of Change (DoC) model based on the analysis of the relationship between structures, institutions and agents or ideas and interests. The DoC approach tries to comprehend the country's political economy environment by identifying the factors or drivers of change that will generate incentives for change over the short, medium and long-term (DFID, 2009). This approach considers the dynamic interaction between three factors, which are structures, institutions and agents or ideas and interests. In this section, we outline what these look like in the context of South Africa's micro-biodigester sector by identifying and analysing factors through a desk review of reports and academic literature.

2.1.Structures

Structures are defined by long-term contextual factors, including economic and social structures, geo-strategic position, natural resource endowment, demographic shifts, climate change and technological progress (DFID, 2009). Structures evolve and change over a long period and are not easily influenced.

The transformation of South Africa into a democratic state after years of apartheid oppression has influenced the power sector through a new policy focus on promoting social equity and improving economic competitiveness (Eberhard, 2017). In 1994, the governance style of the new government was to make policy debate and decisions more visible than the previous government, which concentrated social and economic opportunities in the hand of a white minority (Ibid). The government used to provide cheap and abundant electricity from coal to leverage industrial strategy and economic development (Bischof and Creamer, 2018). South Africa's endowment with coal, biomass, wind, geothermal, hydro and fossil fuels shapes energy sources. The country's power generation capacity is 51,309 MW, and its energy mix is dominated by coal with 38,000 MW as of 2018 (IRP, 2019). South Africa is the seventh-largest producer of coal globally, and 77% of this production serves its energy demand (DMRE). In 2017, coal made the largest exports in the country and accounted for ZAR 61 billion (Mineral Council, 2018). The coal mining sector provides numerous jobs and employs 82,000 workers (Ibid). Although coal has a significant weight in the South African economy, it is not environmentally friendly. The heavy reliance on fossil fuels leads to roughly 450 million tonnes of CO_2 emissions per year and makes South Africa the leading emitter in Africa (IEA, 2017; Roopnarain and Adeleke, 2017). Global technological advances allow for the adoption of cheaper and clean energy and modern power infrastructures.

The power sector faces existing challenges of financial difficulties, lack of energy security, obsolete power infrastructures, power shortages and electricity price hikes which add to the new challenges of grid integration, ownership of assets, regulatory framework and others (IISD, 2020). The state-owned, vertically integrated monopoly utility Eskom has been a major power player in the sector since the 1980s. Eskom is undergoing financial crisis and performance problems due to mismanagement, debt and governance issues (IISD, 2020). Reforms have been proposed to surpass Eskom challenges by unbundling the utility into three separate entities which will oversee the generation, transmission, and distribution of electricity (Ibid).

Efforts and initiatives are being taken to address the sector's issues. For instance, the introduction of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in 2011 changed the configuration of the power system by allowing the entry of new actors and ownership and increase the share of renewable energies into the energy mix. In addition, the 2019 Integrated Resource Plan (IRP) mentions plans to diversify the energy mix by 2030 and reduce the energy sector's carbon footprint. All these initiatives offer opportunities for the development of biogas in the country.

Apart from being a clean source of energy, biogas has the advantages of providing domestic energy to households, improving environmental well-being and increasing agricultural productivity. However, the uptake of the technology in South Africa is low, with approximately 700 micro digesters in the country (Uhunamure et al., 2019). The study on the adoption and use of micro digester in Limpopo revealed that diverse factors impact the adoption of the technology, such as subsidies from the government, ownership of cattle, land and crops, income revenues, socio-cultural aspects and others (Ibid). The causes of the low dissemination of the technology go beyond technical challenges and include 'all-encompassing problems and factors, including human socio-economic, socio-cultural, institutional and environmental characteristics' (Ibid, 2019, p. 269). Economic factors are also significant barriers to the deployment of biogas technologies, such as high investments, low incomes and poverty, and low economic development (Nevzorova and Kutcherov, 2019).

2.2.Agents

Agents refer to internal and external actors who participate in the sector, who are included in or excluded from processes and networks (DFID, 2009). Agents have different levels of influence and include actors from the public, private or third-party sector such as political leaders, business associations, trade unions, foreign governments, regional organisations, donors and multinational corporations, among others. Table 1 below provides a non-exhaustive, selective list of agents related to the micro bio-digester in South Africa.

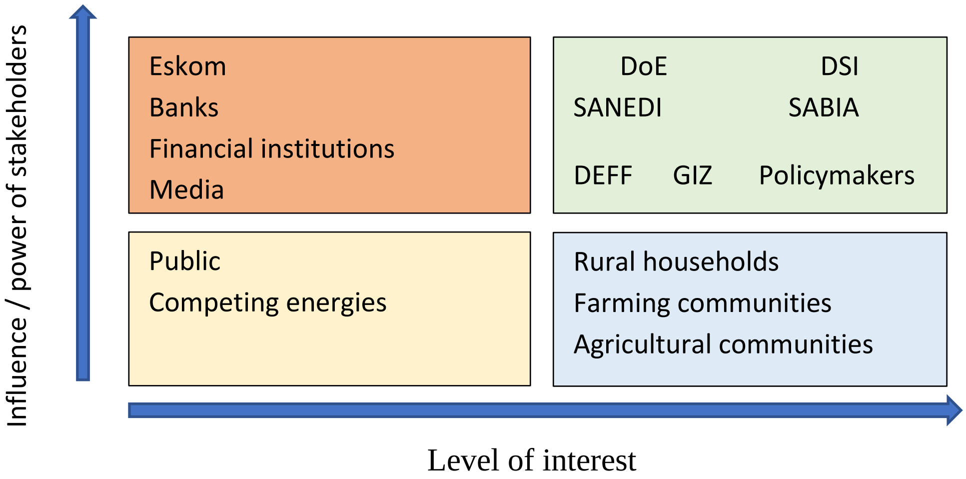
Table 1: list of agents in the micro biogas digester in South Africa

Public sector	Private sector	Third-party sector
Department of Energy (DoE) Department of Science and Innovation (DSI) South African National Energy Development Institute (SANEDI) Department of Environment, Forestry and Fisheries (DEFF) National Energy Regulator of South Africa (NERSA) Eskom Municipalities Licensing and permitting authorities	Biogas SA Agama Biogas Biogas project developers Biogas wholesalers and retailers	Southern African Biogas Industry Association (SABIA) German Cooperation (GIZ) Development Bank of Southern Africa (DBSA) International institutions

Source: Author compilation

These agents have a different level of interest and influence in the sector, and we use the power/interest matrix to illustrate that. Eden and Ackermann (1998) developed this matrix to analyse stakeholders' interest in an organisation or issue and stakeholders' power to affect the organisation or issue. Actors are classified in the matrix based on their involvement, actions, and achievements in the micro digester sector. The desk review of materials helps obtain information on actors 'activities. Figure 1 below illustrates the classification of a couple of stakeholders in the micro digester domain in South Africa.

Figure 1: Influence/Interest matrix of micro digester stakeholders in South Africa



Source: Adapted from Eden and Ackermann, 1998, p.349

- High influence and high interest: manage closely
- Low influence and high interest: keep informed
- Low influence and low interest: monitor
- High influence and low interest: keep satisfied

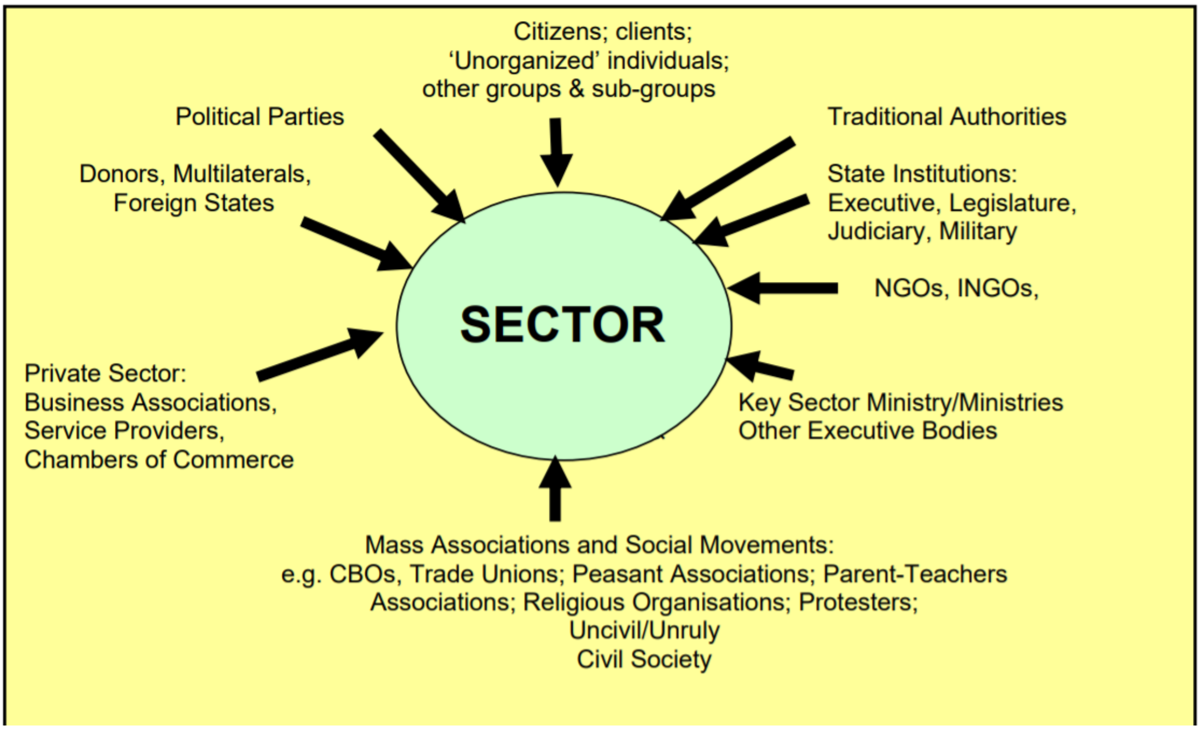
Actors from the public sector are comprised by the Department of Energy (DoE), Department of Science and Innovation (DSI), South African National Energy Development Institute (SANEDI), Department of Environment, Forestry and Fisheries (DEFF), National Energy Regulator of South Africa (NERSA), Eskom, municipalities and policymakers among others. SANEDI shows high interest and high influence in the micro digester by promoting the technology through various initiatives and collaboration. SANEDI developed its expertise in micro digester projects by implementing the Working for Energy programme over the past five years (SANEDI, 2020). The institute organises renewable energy research, including biogas research and collaborates with academic institutions (Roopnarain and Adeleke, 2017). Eskom has a high influence for its ability to affect the micro digester sector positively or negatively. Eskom's rebate scheme for small-scale renewable energies could help promote the technology in the country (Roopnarain and Adeleke, 2017). While Eskom grid-feeding regulations limit the movement of excess biogas energy, this may reduce the adoption of the technology (Greencape, 2017).

Actors from the third-party sector refer to non-profit organisations, voluntary and community organisations, non-governmental organisations. In the South African micro biogas digester, these actors are the Southern African Biogas Industry Association (SABIA), German Cooperation (GIZ), Development Bank of Southern Africa (DBSA) and International institutions, among others. SABIA also demonstrates high interest and high influence in the micro digester sector by mobilising a network of actors. SABIA represents a community of 1500 stakeholders in South Africa and lobbies for legislative changes and policy development (SANEDI, 2020). The association contributed to the organisation of the first South African National Biogas Conference in 2013. It achieved some initiatives such as the incentive scheme for biogas and standards for micro industrial biogas plants (Ibid). The international actor, GIZ, participates in the promotion of micro digester in South Africa by implementing various projects. GIZ facilitates the National Biogas Platform through the South African-German Energy Programme (GIZ-SAGEN) (GIZ, 2015). These overall agents have a great potential to make a difference in the micro-digester sector and increase collaboration between all stakeholders.

Actors from the private sector are constituted by companies like Biogas SA, Agama Biogas, Biogas project developers, Biogas wholesalers and retailers, among others. Their high interest and high influence in the micro bio-digester is seen through the implementation of projects, even though they encounter cumbersome administrative procedures when implementing projects. The direct beneficiaries of micro bio-digesters are rural households, farming and agricultural communities, among others. These actors have a low influence and high interest in the micro digester technology. These groups and individuals benefit from installing the technology, especially in rural households facing an energy crisis. Domestic biogas directly affects the household's daily life (Ortiz et al., 2017). In addition to receiving a new cookstove, the beneficiaries become producers of energy (Ibid). The identity and number of agents of the micro bio-digester have evolved over time with the participation of public, private and third-party sector actors. The creation of the National Biogas Platform allows for a better organisation of agents in the sector.

The collaboration between a wide range of agents is crucial for the development of the sector. Figure 2 below illustrate categories of agents to consider when developing a sector.

Figure 2: Sector stakeholder map



Source: Overseas Development Institute Analytical Framework for Political Economy Sectors

Effective engagement between all actors from the private, public, third-party sector will facilitate the diffusion and adoption of biogas technologies.

2.3. Institutions

Institutions can be formal or informal in terms of constitutional rules for the former and political, social and cultural norms for the latter (DFID, 2009). This factor helps understand how things get done between formal rules and informal power relations.

South Africa went through radical transformations of the social, political and economic institutions during the democratic revolution. This has shaped the country's national development vision along with social and political rights, socioeconomic progress, reconciliation and national unity. The government sets its current vision in the National Development Plan (NDP) 2030 and shows commitment to provide a decent standard of living to all South Africans through the elimination of poverty and reduction of inequality and unemployment (IRP, 2019). Plans to improve the energy sector, reduce environmental pollution and provide socially equitable, reliant and efficient energy services are also showcased in the NDP. The institutional interest in bioenergy is highlighted in a couple of policies, from the white paper on renewable energy in 2002 to the NDP in 2011. Although there are a couple of existing policies addressing biogas, the policy framework needs to be strengthened to enable the sector's development.

Substantial financial support from the government is necessary to deploy micro bio-digesters in rural areas of South Africa. Sovacool (2013) explains that pro-poor, multi-institutional models, including end-users microfinance, are needed to overcome renewable energy technologies' capital costs. Low incomes and the spread of poverty constitute hurdles to adopting biogas technologies (Nevzorova and Kutcherov, 2019). Providing subsidies, soft loans, and financial support programmes to adopt micro bio-digesters are encouraging incentives for potential household consumers.

Cultural barriers to the use of micro bio-digester are the lack of public participation, consumer interest, and acceptance, among others (Nevzorova and Kutcherov, 2019). Low level of knowledge on the technology and resistance to change, lack of information and low level of education are also part of these barriers (Ibid). Stigmatisation and incompatibility with local and traditional beliefs, religious views on cleanliness, and animal excrements prevent the diffusion of technology. Potential household consumers should be included in the designing process of micro biogas digester projects to mitigate socio-cultural barriers. Co-designing is a success factor in implementing rural energy interventions (Blanchard et al., 2017).

3. Conclusion and Recommendations

The analysis of the political economy of the micro biogas digester in South Africa demonstrated the political will and dynamic to develop the sector and highlighted the obstacles. The observation of structural issues revealed the influence of historical events on the country's economic and political settings and the energy sector. The exploitation of coal dominates economic activities, and this requires alternative economic strategies due to contemporary changes. These issues shape the political structure and institutional environment of the country. Key players from the public, private, and third-party sectors have high interests in developing the biogas sector and contribute to efforts and initiatives to leverage mobilisation. Several factors hinder the uptake of the technology, such as economic, socio-cultural and institutional barriers.

We recommend:

- To consider the interests and incentives of key agents and influential actors for their ability to shape the dynamic of the biogas sector
- To increase dialogue between stakeholders to enable working relations and build a coalition for change

- To develop coherent and clear policies
- To share information on micro biogas digesters and best practice examples of successful biogas projects
- To engage with a wider range of actors such as traditional authorities and the media to promote the acceptance of the technology and communicate on the benefits of the technology
- To utilise inclusive participation through co-designing with potential consumers
- To provide subsidies and financial support for the development of the biogas sector

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Annex 5: Policy analysis

This input draws on the policy experiences related to the use of biodigesters for methane production worldwide to inform sector development in South Africa. The different country policies reflect the issues and challenges that pertain to the respective contexts and socio-economic environments. Some observations are drawn from the different cases and applied to the South African context.

1. Introduction

According to some estimates, there are about 50 million installed biodigesters globally, most of which are located in Asia, particularly in China, India, Nepal, Vietnam, Bangladesh, and Cambodia (The World Bank, 2019; Clemens et al. 2018). Studies suggest that biodigesters are suitable for energy generation in rural and poor farming environments as they foster improved manure management resulting in financial, health and environmental benefits (Stockholm Environmental Institute (SEI), 2019). Despite the relevance of biodigesters and their benefits for the African context, the dissemination of the biodigesters in the continent has been both constrained and uneven (The World Bank, 2019; Nape et al., 2019).

The extent to which biodigesters are adopted in a country is dependent, among other things, on the availability of policies that support their adoption. Naturally, an enabling policy that facilitates the provision of the necessary support and resources tends to promote the adoption of these systems. This is particularly true for small-scale farmers in poor rural environments. A policy analysis for biodigesters, therefore, is important for understanding the broader political economy that determines the extent to which this technology is likely to succeed in any given environment.

Ultimately, this study seeks to explore the viability of the technology in the South African situation. The lessons derived from comparable experiences elsewhere are leveraged to contribute to a better understanding of the factors that can promote, inhibit or otherwise impact the implementation of biodigesters locally. To this end, this policy review begins by analysing policies across the world before turning the spotlight back on South Africa. There are many ways in which policy is defined. This review takes a broad view of policy, including statements of intent, principles, legislation, regulations, procedures, administrative actions, incentives, or protocols to guide decision-making to achieve set outcomes.

2. The international policy environment for bioenergy production

Policies that directly address biodigesters are generally uncommon. References to biodigesters are often accommodated in broader policy frameworks such as energy, sustainability and agriculture. In many cases, policy references to biodigesters simply do not exist and can only be inferred from related topics. This posed a challenge for the review. Nevertheless, an effort was made to identify policies that refer to biogas production rather than the associated issues. Where it was not possible to obtain relevant policies from official publications, published scientific papers and project reports constituted viable alternative sources.

2.1 Global multilateral institutions

Despite the successes in rural environments of places such as China, it took a while for multilateral development institutions to appreciate the role of biodigesters in economic development and incorporate them in policy for application in appropriate environments. The 2030 Agenda for Sustainable Development of the United Nations adopted in 2015 provides multiple policy touchpoints wherein biodigesters can directly contribute to achieving the majority of the 17 sustainable development goals (SDGs). A mapping of these touchpoints is found in **Annexure A**. In this policy review, references are made to the role of biodigesters in addressing poverty and hunger (SDGs 1 and 2) by empowering communities to generate their energy and fertiliser. Depending on the policy objectives in various countries, biodigesters address the other SDGs indicated in the diagram.

The development of the SDGs has helped to focus the work of international organisations around sustainable energy. The Food and Agriculture Organisations (FAO) developed a guideline to assist policymakers, primarily policymakers, in developing bioenergy options that safeguard food security (FAO, 2014). This includes exploring options for the use of agricultural residue for the production of energy, including biogas. In the World Bank, biodigesters have mainly been supported under carbon finance to implement programmes in China and, more recently, as part of a portfolio of programmes of the Clean Development Mechanism (CDM) for promoting energy access by the Carbon Initiative for Development (Ci-Dev) Trust Fund in Burkina Faso, Ethiopia and Kenya (The World Bank, 2019). More is said about these programmes in the next section. The relevant policy instruments and programmes of the various international organisations are listed in **Annexure B**. The list, which is meant to be illustrative rather than exhaustive, indicates how solutions from various organisations can leverage biogas production to contribute to development.

The Global Methane Initiative (GMI) is an international public-private partnership focused on reducing barriers to the recovery and use of methane as a clean energy source. GMI (2014) provides technical support to deploy methane-to-energy projects worldwide that enable countries to launch methane recovery and use projects. GMI provides technical support to deploy methane-to-energy projects worldwide and has enabled Partner Countries to launch hundreds of methane recovery and use projects. Some of the studies conducted by GMI are being cited further down this report.

2.2 Asia

The proliferation of biodigesters in China is a direct response to the government policies that promote and support a nationwide biogas programme in the country (Aamodt & Winqin, 2020). According to these authors, close to 40 million rural households benefit from biodigesters in that country. More than 72,600 biogas plants deal with agricultural wastes, of which 4,641 are large-scaled biogas plants, 22,795 are medium-scaled biogas plants, and 45,259 are small-scaled biogas plants, with respective total capacities of 3.60 million, 3.07 million and 1.90 million cubic metres in 2014 (Mathias, 2014). The Chinese government employed a variety of policy instruments to achieve higher uptakes of the technology, including the imposition of price controls on certain materials to assist the poorer households in installing biodigesters; and providing special low-interest loans for households that were willing to expand their livestock farms and install a biogas system (Solh, 2010). The 2006 Law on Renewable Energy decreed the development of markets for renewable energy, planning and exploitation of renewable energy sources, support for industry and technology, sharing costs, prices and investment capital, and design appropriate energy taxes (ISPONRE, 2009 as quoted by Solh, 2010). The country's policies helped to accelerate the uptake of biodigesters in China, as demonstrated by Aamodt and Winqin (2020) in their survey of laws, policies and guidelines that helped to shape the development of the Chinese biogas sector to support, in particular, the economic development of poor and marginalised rural farmers. The pivotal role of policy in the development of the Chines biogas sector is also referenced by Chen et al. (2012), Jiang et al. (2011) and Mathias (2014). Some of the key policies spanning the energy, environmental, agricultural and economic sectors are identified in **Annexure C**.

In the case of Bangladesh, the policy objectives are different to those discussed above. Bangladesh's Livestock Manure Management (ILMM) policy and action plan were developed by the Ministry of Fisheries and Livestock (MoFL) to address the environmental and health problems associated with livestock and manure production on farms and to increase the sustainability of Bangladesh's livestock sector (MoFL 2016 as quoted by the Stockholm Environmental Institute (SEI), 2019). The policy encouraged livestock farmers to adopt biodigesters and create value-added manure products, thus contributing to the environment's preservation. The policy achieved this by, among other things, helping farmers to set up societies and the construction of "community" biodigester plants and environment-friendly manure storage and treatment facilities (SEI, 2019). This saw the cooperation of government, non-governmental organisations and the private sector in setting up micro-finance lending facilities and offering technical support for small-scale farmers to support the adoption of biodigesters across the country (SEI, 2019).

Cambodia’s National Biodigester Programme (NBP) began in 2006 as a joint development between the country’s Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Netherlands Development Organisation (SNV). The focus of Cambodia’s biodigester programme was to disseminate domestic biodigesters to farming households as an indigenous, sustainable energy source through the development of a commercial, market-oriented, biodigester sector in eight selected provinces of Cambodia, according to the report by the Swiss Association for Quality and Management Systems (SQS, 2011). The biodigesters were established for small rural farmers to treat animal and human waste to produce a clean, renewable cooking and lighting fuel, biogas, and the treated waste to be used as a potent but safe organic fertilizer. Hivos, another Dutch NGO, joined the consortium in 2007, providing carbon finance. The set-up of the NBP has some policy and governance characteristics that are worth further exploration below.

In terms of the memorandum signed with the Kingdom of Cambodia, the NBP was set up in such a way that the SNV was given a fixed term to set up the initiative with an “expiration date” built into the agreement, upon which ownership would revert to the government (Hyman & Bailis, 2018). The NBP's goals were to create a self-financing biodigester market in Cambodia that would install 20,000 biodigesters between 2006–2012; double that number by 2018 while ensuring good maintenance of all the installed biodigesters; and finally, ensure the associated benefits of the bio-slurry fertilizer and the household lighting functionality (Hyman & Bailis, 2018). There was a lot of policy emphasis placed on financial sustainability and national capacity building. Under the agreement, SNV provided a Senior Advisor for a five-year term who planned for his departure, right from the beginning, by hiring a Cambodian counterpart. Programme commitment was ensured at the highest levels of government in that a Steering Committee initially governed the NBP with representatives from MAFF and SNV (Hyman & Bailis, 2018). Despite all the support and some success, the NBP has not been spared some challenges worth learning from (Hyman & Bailis, 2018).

A report by the UNEP-DTU Partnership traces the development of biogas in Vietnam from the 1960s (UNEP-DTU, 2017). According to this report, there was “no legal document, institutional framework or policy specifically regulating the development of biogas plants at farm-scale in Vietnam (UNEP-DTU, 2017). The Ministry of Agriculture and Rural Development (MARD) initiated its national biogas programme in 2003 with support from the Government of the Netherlands through technical support from SNV (Netherlands Development Organization). The key objective of installing small-scale biogas digesters in households was to reduce GHG emissions (UNFCCC, 2013). The first phase was completed with a total of 18,000 biogas units having been installed nationwide. The long-term aims of the programme were to: promote biogas systems as a source of renewable energy production in an environmentally compatible and economically viable way; increase the awareness of prospective livestock smallholder households and extension workers on the full extent of the potential costs and benefits of domestic biogas installations; strengthen human capacity on all aspects of management of domestic biogas installations; and strengthen the institutional infrastructure for coordination and implementation of sustained dissemination of domestic biogas at national, provincial and district levels (UNFSCCC, 2013).

The above survey of a few Asian countries suggests that there were different policy emphases in the implementation of biodigesters, with further analysis in table format **Annexure C**. where there are no specific policies for biogas production, the policy objective and instruments are derived from the programmes that are implemented in the country, such as in Vietnam. However, the environmental benefits were recognised across the board. In some jurisdictions, the programme privileged other imperatives such as health, skills development, rural development, economic development and energy security. Policy support systems also took on different guises, depending on the farmers' needs and the country's prevailing circumstances. Likewise, programme governance protocols varied accordingly, reflecting different levels of government participation.

2.2 The Americas

Bioenergy programmes take on different forms in different countries depending on the prevailing needs and opportunities. According to the World Bank, the choice of the instruments is usually informed by the bioenergy sector's relative importance to the country's overall energy security, the level of technological advancement and the level of organization or influence of the players in the sector (The World Bank, 2019). Brazil is a case in point in this respect.

In 1975, Brazil launched the world's first major government-backed ethanol programme, Proalcool, under Decree No. 76953, which set the country a pioneer in national regulatory efforts for bioenergy production (The World Bank, 2019). When global oil prices were exceedingly high, Proalcool was initiated to promote the production of ethanol from sugar cane to meet rising energy needs in transport sector fuels and ensure energy security for the country. Since then, Brazil has been a trailblazer in supporting bioenergy production through setting enabling legislation and policies. Brazil's bioenergy policies have nevertheless been criticised for privileging a single crop and marginalising small farmers (Sakai et al., 2020). There is also vast potential for biogas production in Brazil from animal waste owing to the country's prolific pig and cattle farms (Mathias, 2014). The policy initiatives to respond to this potential are outlined in **Annexure C**.

As is the case for Brazil, the development of bioenergy policies and legislation in the United States was triggered by a very particular need. In the case of the US, it was to support the country's farmers in the face of collapsing prices for agricultural produce by developing an alternative market for biofuels generated from maize in the energy sector. A broader policy framework for bioenergy was laid out in great detail in the 2016 Billion-ton Study of the country's Department of Energy (US DoE) to evaluate the potential economic availability of biomass resources using the latest available yield and cost data. In calculating estimates of the total available biomass, the study went beyond the biomass-derived from forestry, agriculture and waste, and included algae grown in open pond-raceways systems for bioenergy production (US DoE, 2016).

Mexico's renewable energy programme was premised on the country's General Law for Climate Change which set GHG reductions goals at the same level as industrialized countries. According to the National Development Plan (NDP) formulated during 2006–2012, the pathway biomass energy involved a set of policy guidelines premised on the notion that energy is a resource for human development in agreement with the United Nations Development Program (Alemán-Nava et al., 2014).

The Energy Reform in Mexico, which began in 2014, was implemented to increase energy security, minimize the negative effects of fossil fuel dependence, and minimize environmental impacts (Tsydenova et al., 2019). The Energy Reform consists of introducing the Electricity Industry Law and the Federal Commission of Electricity Law, along with other regulations arising from the amendments to articles 25, 27, and 28 of the Mexican Constitution. This legal framework created better conditions for renewable energy sources; set the goals to generate 35% of clean energy by 2024 and reduce greenhouse gas emissions by 22% by 2030 (Tsydenova et al., 2019). Before the reform, most of the electricity market functions were concentrated at Comisión Federal de Electricidad (CFE), which is the state-owned electric utility of Mexico (Tsydenova et al., 2019). Not unlike the recent developments in South Africa, the policy reform introduced new stakeholders to the market and gave more freedom to the energy generators to compete against the state companies for the production, distribution, and retail of energy.

2.3 Europe

According to Zhu et al. (2019), Europe is the world leader in biogas production, accounting for more than half of global production, followed by Asia with a 30% share. The European Union (EU) legislative framework regarding issues that relate to biogas production has played an important role in shaping the industry, particularly by improving the economics of anaerobic digestion (Zhu et al., 2019).

The policy foundation for progressive development in renewable energy production in the EU was laid in 1997 when the European Council and Parliament adopted the White Paper for a Community Strategy and Action Plan (Scarlat et al., 2018). This was followed by a series of plans and commitments regarding climate change and clean energy. In 2007, the European Commission adopted an integrated Energy and Climate Change package on the EU's commitment to change, including a commitment to achieve at least a 20% reduction of GHG emissions by 2020, compared to 1990 levels and a mandatory EU target of 20% renewable energy (Scarlat et al., 2018). The 2009 Renewable Energy Directive(RED) on the promotion of renewable energy sources sets further targets, including provisions to facilitate the development of renewable energy, such as detailed roadmaps and measures taken to reach the RES targets and develop the energy infrastructure.

On a longer-term basis, the EU has adopted more stretching and ambitious targets in the Energy Roadmap 2050. The document explores possible pathways for a transition towards complete decarbonisation of the energy system (Scarlat et al., 2018). Other major policies include the bioeconomy strategy in 2012 and the Directive 2015/1513 which, significantly, sets a limit of 7% of the final consumption of energy in transport in 2020 for the biofuels produced from food or feed crops grown for energy purposes on agricultural land (Scarlat et al., 2018). The EU member states are also part of global agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC). The EU has already adopted a 2030 Framework for climate and energy and has set EU-wide targets and policy objectives for 2030 in a whole range of pertinent aspects (Scarlat et al., 2018).

2.5 The African experience

The use of biodigesters has great potential in Africa. The World Bank estimates that as many as 18.5 million households could benefit from this technology in Sub-Saharan Africa. The Constitutive Act of the African Union makes provision for cooperation in environmental matters, energy and agriculture. In 2013 the AU developed a pan-African bioenergy agreement. The Africa Bioenergy Policy Framework and Guidelines followed three years of intensive research, consultation and collaboration between the AU Commission and the United Nations Economic Commission for Africa (UNECA). The framework aims to support national policies and initiatives by harmonising policies at a regional level and promoting cross-border trade in bioenergy. To guide member countries on bioenergy approaches, the Africa Bioenergy Policy Framework contains details on the following topics:

- Understanding Bioenergy in the African Context
- Key Bioenergy Issues and Policy Considerations
- Process of Sustainable Bioenergy Policy Development
- Bioenergy Policy Implementation Action Areas
- Monitoring and Evaluating Implementation
- Implementing the Bioenergy Framework and Policy Guidelines

One of the most ambitious biogas initiatives in the continent is the Biogas Africa Initiative. In 2007 it set a target of implementing domestic biogas plants for two million households throughout the continent (van Nes & Nhete, 2007). The programme would be funded through microcredit, loans and cash contributions which will account for 0.9 billion Euros, supplemented by a grant of 600 million Euros to subsidise purchasing costs, promotion, training, quality control, promotion and management. The initiative focuses on countries and regions across Africa with the best market opportunities.

According to the project brochure, some of the principles guiding the initiative are:

- investment and business opportunities to benefit both governments and households;
- consumer confidence premised on guaranteed effective service delivery, maintenance and safety;
- local technicians providing service on a willing seller and willing buyer basis;
- implementation to focus on countries and regions in Africa with the best market opportunities;
- Management of the initiative will be lean and independent and will provide leadership and a funding channel for untied grants, facilitate the exchange of knowledge, mobilise partnerships and encourage innovation and market research.
- Governments will play the public role corresponding to a market-oriented approach by creating an enabling environment for the market to develop and succeed, providing grants and tax breaks, drawing up standards and legitimising the programme.
- Local organisations will play specific roles in promoting, effective maintenance, sustaining and mobilising consumer trust, service delivery and household confidence and interest.
- Local businesses will be crucial for the initiative; they will mobilise the supply side. Effective and transparent governance of local entrepreneurship will ensure sustainable and commercially attractive local biogas business.
- The Advisory Committee and African Leadership Group will advise the Board on the orientation of the Initiative at policy levels, not at an operational national level.

The strong emphasis on financial success and an openly market-oriented approach set the initiative apart, particularly in Africa. The rest of the principles provide some options worthy of consideration in similar endeavours. Annexure C provides summaries of the policies, priorities and instruments of some of the countries in Africa, including Benin, Ghana, Mali, Mozambique, Tanzania and Zambia.

3. South Africa

It can be argued that the policy foundation for the dissemination of the biodigesters was laid with the release of the White Paper on the Promotion of Renewable Energy and Clean Energy Development in 2002 by the Department of Minerals and Energy (DME, 2002). This is so even though biodigesters and their opportunities for biogas production are not mentioned in the White Paper. Nevertheless, the policy is significant in that it highlighted some of the relevant imperatives, including the energy crisis in rural environments and the role that biomass and other waste can play in alleviating the situation. Wood is still the main source of energy for most rural households. Regarding manure and litter, the White Paper observed:

> *“The potential exists to utilise the manure and litter from livestock to generate methane gas through anaerobic fermentation in biogas plants. Most cattle farms in South Africa are free-range, and the poultry and pig farms have large amounts of manure available on site. An assessment is required to see if the litter and manure from these farms can be*

used in biogas generators or burned in incinerators on a scale that would warrant classification as an IPP." (DME, 2002, page 9)

While the thrust of the policy, in the main, was on scale production, the direct reference to the potential for biogas generation from animal manure was an important milestone in policy development.

There have been important policies preceding and following the White Paper on renewable energy discussed above. The White Paper on Energy Policy and the National Environmental Management Act of 1998 stand out in importance as they refer more directly to biomethane generation. Since 2002, the Biofuels Industrial Strategy of the Republic of South Africa has been adopted, preceding the significant Renewable Energy Independent Power Producer Procurement Programme and the National Development Plan adopted in 2011. The relevance and application of these and other policies are outlined in Table 1.

Policy	Date	Purpose	Relevance	Application
White Paper on Energy Policy	1998	Sets new priorities for South Africa's energy policy	Laid foundation for exploration of diverse energy sources for increased energy security	Precursor to the White Paper on Renewable Energy
National Environmental Management Act (NEMA)	1998	To provide for co-operative, environmental governance by establishing principles for decision-making on matters affecting the environment	NEMA enables a series of Special Environmental Management Acts (SEMA's) that address specific facets of environmental management that are relevant to biogas production	Sets standards regarding the location and construction of biodigesters
White Paper on Renewable Energy	2002	Sets out Government's principles, goals and objectives for renewable energy	Committed Government to several enabling actions to ensure that renewable energy becomes a significant part of its energy portfolio	Specifies potential to utilise the manure and litter from livestock to generate methane gas through anaerobic fermentation in biogas plants
Biofuels Industrial Strategy of the Republic of South Africa	2007	To stimulate rural development by creating sustainable income-earning opportunities in biofuels farming	Generate interest on the part of farmers to participate in energy generation	Recommended blending levels for biofuels
Renewable Energy Independent Power Producer Procurement Programme **(REIPPPP)**	2011	Advance energy security for South Africa through the participation of the private sector in renewable energy production	Actioning of the country's commitments to clean energy production Demonstrable facilitation of private sector participation in energy generation	Although the focus is on electricity generation, the programme offers valuable lessons on how to diversify energy sources, including the production of biogas
National Development Plan Vision 2030	2011	Provides a comprehensive multisectoral long-term plan for the country	Outlines country's commitment to a low carbon economy	Outlines a phasing and sequencing of key initiatives for greater energy efficiency and carbon emissions

Table 1: Some key South African policies relevant to bioenergy production

4. General Observations

The above survey indicates that there has been an increasing intensity in the adoption of policies that support the implementation of biodigesters across the world. However, policy seldom translates perfectly into implementation. In this section, we explore the factors that either promote or inhibit the growth, spread and sustained use of biodigesters in areas where the technology could add social and economic value. While there may be many factors that could limit or enable the growth of biodigester technology, this discussion addresses only those that pertain directly to policy.

4.1 Policy focus and definition

The promotion of grassroots production of biogas is often lost in the definition of terms such as “biofuels” and “bioenergy” in the accompanying policies. Depending on the adopted definition, the leading government authority vested with the development and implementation of the country’s biofuels policy may strengthen or alienate the role of biodigester-produced biogas in the bioenergy enterprise.

Bioenergy is generally defined as energy that is generated from biofuels, while biofuels, in turn, are defined as fuels of biological origin (FAO, 2000). In this definition, it should be straightforward to list biogas alongside the likes of wood, charcoal, livestock dung, bioethanol and microbial biomass as examples of biofuels. However, many country biofuels strategies make no reference to biodigesters and the role of small farmers in biofuels production. The international policy review conducted by the FAO suggests that country policies and definitions of biofuels often reflect the idiosyncrasies that derive from the challenges that are particular to that country (FAO, 2000).

The oversupply of agricultural produce in the United States in the 1980s prompted the government to promote biofuels, particularly ethanol, made from maize. Therefore, the country’s biofuel policies focused on revitalising the agricultural sector and opening new market opportunities for struggling farmers (FAO, 2019). The promulgation of the Clean Air Act and the Reformulated Gasoline Programme in the early 1990s, and the Energy Policy Act in 2005 provided further support for the sector. Similarly, in Europe, the EU developed the Biofuels Strategy to mitigate the implications of climate change by diversifying fuel supply sources through creating opportunities for agricultural products (FAO, 2019). Over this period, a few other countries, including South Africa (DME, 2007), embarked on similar biofuels strategies. These tended to concentrate on bioethanol production to exclude biogas and small farmers in their biofuel policies.

The narrow definition of biofuels in policies and strategies to focus either exclusively or largely on bioethanol robbed the biogas production the attention it needed, particularly concerning the development of small farmers and rural households. Without an enabling regulatory framework to encourage private investment in small-scale biogas production industries of the kind and extent seen in countries in Asia, it is virtually impossible to realise a broad adoption of biodigesters to contribute to a country’s energy mix.

Narrow definitions are also likely to be realised through sector biases. This refers to the tendency of policymakers to view the world through a lens that is dominated by a sectoral perspective. As a result of sector bias, “biofuels” assume a particular meaning in the mind of an energy policymaker, as opposed to a counterpart in the agriculture or rural development sector. As demonstrated in the above policy review, the role of small farmers and domestic biodigesters is a lot more prominent in the policies generated by the ministries responsible for agriculture or the environment than those that oversee different mandates.

4.2 Availability of an enabling policy framework and supporting instruments

In Africa, the poor adoption of biodigesters to augment the energy needs of small farmers has been laid squarely on the door of governments, considering that governments are responsible for enacting public policies. Nape et al. argue that the failure of African governments to promote widespread adoption of this technology "is due to the lack of energy policies that support biogas technologies or renewable energy initiatives, and a lack of substantial investments in renewable energy" (Nape et al., 2019). When there are no policies to support the adoption of biodigesters, naturally, the support instruments will not be available, rendering any hopes of broad implementation stillborn (Bensah & Brew-Hammond, 2010).

The adoption of biodigesters by small farmers in developing countries only grows appreciably when there is substantial support from governments and aid agencies (Bui Xuan et al., 1997). The continuation of the support is so critical that when it is removed or reduced, the number of biogas plants built each year falls dramatically, as observed in several cases (Ellis & Hanson 1989; Qiu et al., 1990; Desai 1992). The availability of continuous support makes it possible to reduce technology acquisition costs so that it becomes accessible to a greater number of people, as was found in the case of Tanzania (Rutamu, 1999). A study conducted by the Global Methane Initiative in different countries worldwide (see **Annexure D**) reinforces the importance of policy incentives to support the uptake of bioenergy generation (GMI, 2014).

In a study conducted among farmers who had biodigesters installed in Tanzania, Rutamu (1999) found that a certain threshold number of biodigesters is necessary to justify costs of extension and follow-up before the technology is disseminated enough for home-grown village technicians to solve problems related to repair and maintenance. In this community, it was found that when the biodigesters are built on a cash basis, affording a small margin to allow the construction to continue in a revolving manner, eventually each technician was able to buy a bicycle used to allow the mobility to provide extension services to users (Rutamu, 1999). The take-home point in this observation is that it is advantageous to configure, within the fabric of a policy, opportunities for the emergence of mutually reinforcing outcomes that help to propel the implementation of the intervention.

The importance of government policy and sustained support is further enhanced in a multinational study conducted by the World Bank. The study found that the absence of guiding policies and a supportive regulatory framework creates uncertainties that discourage private investment (The World Bank, 2019). On the other hand, government support can contribute to awareness and regulation, support sector development and create the trust needed among end-users for stable demand growth (The World Bank, 2019).

4.3 Unintended consequences

In Bangladesh, as discussed above, the policy intended to promote the setting up of societies that would embark on jointly funded projects with community-owned biodigesters. However, the study conducted by the Stockholm Environmental Institute found that "while there were some large capacity biodigesters, none were collectively owned or managed by small-scale or landless farmers" as envisaged by the Integrated Livestock Manure Management (ILMM) policy and action plan (SEI, 2019). Furthermore, the same study found no community-based structures for the collective installation, ownership and operation of community biodigesters. There were also no loans provided to self-organised groups of poor farmers in any form of association as anticipated by the policy. Instead, where there was a semblance of community cooperation, it took the form of a lead-farmer financing model, where a mid-sized biodigester would be owned and managed only by the lead farmer while the benefits were shared among the farmer's community (SEI, 2019).

The above is just one instance where implementation diverged from the policy intent. It is exceedingly difficult to plan for every eventuality in the dynamic of complex social systems. In the case of Bangladesh, the emergent arrangements in the community were accommodated and supported. This level of flexibility in programme design is essential when multifaceted and multi-stakeholder programmes are concerned. More importantly, this highlights the importance of community participation in policy and programme design so that local knowledge can inform choices and priorities.

4.4 Policy adaptability

The production of biogas via anaerobic digestion, on-farm micro-biodigesters, is a complex albeit small-scale undertaking. It is complex because it attempts to address several challenges simultaneously, such as health and safety in the handling of on-farm animal waste, environmental sustainability in producing renewable energy, and economic development in attempting to produce biogas to supplant traditional energy sources. In addition, a new initiative must anticipate and derive lessons from experience as implementation unfolds. Therefore, to be truly transformative, policies should be not only effective but also adaptive and be able to “change the conditions of change” (Pereira-Querol et al., 2014). To achieve the latter, policies require proven mechanisms for adaptive learning to accommodate changes in implementation that will encourage ongoing learning and the capacity to undertake tactical shifts that will turn failure into success.

Therefore, a key message from the above wide-ranging policy review and analysis is that biogas production models should not be based on pre-determined, universally applicable biogas production forms or solutions. Instead, they should only provide high-level generalisations concerning key developmental objectives and principles, which can be translated to concrete solutions in a variety of environments in any locality.

4.5 Policy coherence

Bioenergy production is an undertaking that is multifaced and multi-layered, as demonstrated by the mapping of the prominent policy imperatives that pertain to bioenergy production against the United Nations Sustainable Development Goals (SDGs) in **Annexure A,** which shows that biodigesters applied to contribute directly to the achievement of at least 12 of the SDGs. The country case studies covered above demonstrate that bioenergy production through anaerobic distillation draws from multiple sectoral policies. This is further collaborated by a GMI (2014) study that found in many countries the prominent role of nutrient management, manure storage, air and water emissions in addition to agricultural concerns, as illustrated in **Annexure E**. This presents the challenge of maintaining coherence between the various policy objectives, actions and partners involved in the initiative (Ebba, 2016). When active attention is not given to addressing policy conflicts and dilemmas, policies can undermine one another. This scenario has to be avoided at all costs.

5. Implications for sector development

The above policy review and analysis presents several implications for the implementation of home-based biodigesters in rural settings.

- There is a need for policies that directly address the role of small farmers in bioenergy production and consumption. The policies should be supported by appropriate incentives and technical support to promote wider adoption and enduring implementation of the biodigester technology.

- The assumptions that are made in policies often don't materialise in implementation. This calls for grounded policies that consider the opinions and lived experiences of the local people, as discussed in the case studies above.
- Given the multisectoral interest in bioenergy and the propensity for a blinkered perspective toward development priorities, it is imperative to craft precise definitions and earmark a clear focus to foster comprehensive and balanced programmes.
- Policies and programmes should be flexible and dynamic in their design to respond adaptively to the practical realities obtained in different communities.
- For biodigesters to make good on their multiple touchpoints with the SDGs (see **Annexure A**), it is essential to adopt a systems perspective in programme design that will foster coherence with all associated initiatives and partners in development.

6. Conclusion

There is no shortage of public policies and development initiatives that broadly promote energy diversification in the wake of growing global concern for climate change and environmental sustainability. However, while most policies address various aspects of renewable energy generation, including biofuels, they seldom address the role of small farmers in rural communities in producing biogas from animal waste for their own consumption. The poor alignment between energy policies, on the one hand, and the agricultural and environmental policies, on the other, often squanders opportunities for integrated development and the simultaneous achievement of multiple SDGs. The review revealed several policy enablers and inhibitors that apply to the implementation of biodigesters in communities. The implications of these for successful sector development were highlighted.

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Annexure A

Mapping of Biodigester Benefits vs the Sustainable Development Goals

Annexure B:

Global Multilateral Bodies: Policies and programmes that relate to biodigesters

Year	Organisation	Policy/Programme	Perspective	Relevance
2015	United Nations	2030 Agenda for Sustainable Development	Sustainable development	Input to various SDGs
1994	United Nations	United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism	Renewable energy and energy efficiency	Use of biomass for energy generation
2015	United Nations Development Programme (UNDP)	Integrated Solutions	Clean and affordable energy	Biogas production
No date	Global Environmental Facility (GEF)	Renewable Energy and Energy Access	Climate change adaptation	Biogas production
2014	Food and Agriculture Organisation (FAO)	Bioenergy and Food Security Approach	Energy-food nexus	Biogas production
2013	United Nations Environment Programme (UNEP)	Global Energy Efficiency Accelerator Platform	Renewable energy and energy efficiency	Waste to energy for clean cooking
2016	World Bank	Environment and Natural Resource Management	Clean, green and resilient growth	Biogas production
2020	World Health Organisation (WHO)	Global Strategy on Health, Environment and Climate Change.	Improve lives and wellbeing sustainably through healthy environments	Clean energy production and waste management
2015	United Nations Industrial Development Organisation (UNIDO)	Promoting Climate Resilient Industry	Energy from waste	Biogas production
2018	United Nations Conference on Trade and Development (UNCTAD)	Policy Brief on Circular Economy	Energy efficiency	Biogas production from waste

2019	Organisation for Economic Cooperation and Development (OECD)	Enhancing Climate Change Mitigation through Agriculture	Mitigation of GHG emissions	Farm-based biogas production

Annexure C:

Summary country policies and programmes that relate to bioenergy

Country	Policy	Main Driver	Support Instruments
China	Renewable Energy Law; Discharge Standard of Pollutants for Livestock and Poultry Breeding; Management Approach for Pollution Prevention of Livestock and Poultry Farms; Criteria for evaluating the environmental quality of the livestock and poultry farm; and Technical Specifications for Pollution Treatment Projects of Livestock and Poultry Farms	Rural development: fertilizers for food production; energy generation	Price controls, low-interest loans, training Support is given through rural small-scale, public, infrastructure projects and rural basic construction projects
India	India Vision-2020, Integrated Energy Policy, National Project on Biogas Development	To meet the demand for energy services of all sectors at competitive prices	Funding and training; government subsidies for the development of family biodigesters of between 30 and 100% of the total price of equipment
Bangladesh	Renewable Energy Policy of Bangladesh	Harness the potential of renewable energy resources and dissemination of renewable energy technologies in rural, peri-urban and urban areas; Enable, encourage and facilitate both public and private sector investment in renewable energy projects; Develop sustainable energy supplies to substitute indigenous non-renewable energy supplies;	Financing facility that is capable of accessing public, private, donor, carbon emission trading (CDM) and carbon funds and providing financing for renewable energy investments; Equipment and related raw materials in producing renewable energy equipment will be exempted from VAT; Investors both in public and private sectors shall be exempted from corporate

		Scale-up contributions of renewable energy to electricity production; Scale-up contributions of renewable energy both to electricity and to heat energy.	income tax for a period of 5 years; Lending procedure will be simplified and strengthened.
Cambodia	Memorandum of Understanding between MAFF and SNV Policy on Biodigester Development in Cambodia 2016–2025	The NBP's original goals were to create a self-financing biodigester market in Cambodia that would achieve the following: 1) install 20,000 biodigesters; 2) ensure that installed biodigesters are well-maintained and continue to be used over the longterm; 3) ensure that the "co-benefits" associated with the biodigester, i.e. the bio-slurry fertilizer and household lighting functionality, are maximized and 4) build national capacity to technically and to financially carry forward the project in the absence of SNV.	The program builds upon the agricultural extension services already established within Cambodia to add training and incentives for biodigester masons, bioslurry experts and program promoters. Buyers receive warranties and access to local technical support. Biodigester financing is facilitated through a special agreement with local banks and credit unions, thus representing an integrated approach to technology dissemination and adoption
Vietnam	Biogas Program for the Animal Husbandry Sector of Vietnam; Quality and Safety Enhancement of Agricultural Products and Biogas Development; The Livestock Competitiveness and Food Safety Project; Low Carbon Agricultural Support Project	Improving the livelihoods and living standards of rural people in Vietnam through exploiting the market and non-market benefits of biogas technology at the household level	Various financing arrangements, training, and other support
Brazil	PROINFA (Incentive Program for Renewable Energy Sources) created by Law 10438/02 Biofuels Law (Law 12.490/11)	To diversify the national energy grid and find regional solutions with the use of renewable energy sources	Subsidies and incentives, which draw on an Energy Development Account funded by end-use consumers through an increase on energy bills (low-income sectors are exempt from this increase)
United States	Billion-Ton Report: Advancing Domestic	Supplying domestic clean energy sources;	Contract length, cost-share, and participation incentive

	Resources for a Thriving Bioeconomy	Reducing U.S. dependence on foreign oil; Generating U.S. jobs; Revitalizing rural economies	
Mexico	General Law for Climate Change; Renewable Energy Sources Law; National Development Plan	Achieve energy security; reduce GHG emissions; human development	A fund for the transition to renewable energy and clean technologies
Argentina	National Programme on Biofuels	Promote the production and sustainable use of biofuels as a renewable source of energy alternative to fossil fuels, with special attention to biodiesel from vegetable and animal oils and ethanol from sugarcane, maize and sorghum; support and advise rural sectors in the development of plants used in the elaboration of biofuels as an opportunity to local and regional development	VAT exemption; corporate tax exemption for three years; excise tax exemption on biofuels
Benin	Biofuels Promotions Strategy	Revival of the agricultural sector; improve the trade balance; increase farmers' income, and reduce pressure on forestry resources.	A favourable regulatory and legislative framework; Establishment of fiscal incentives and support measures; Establishment of a coordination and regulation mechanism for the management of supply chains; Promotion of research and standardization structures
Ghana	Renewable Energy Bill	Promote the use of improved cookstoves and charcoal production technologies; support the regeneration of woody biomass resources; replace petroleum-based fuels; create demand for biofuels, including appropriate pricing of biofuels.	Feed-in tariff scheme; purchase obligations for electricity utilities; fiscal incentives; and the establishment of a Renewable Energy Fund.
Mali	National Strategy on Renewable Energy	Improve access to energy; rationalise the use of existing energy sources; increase the efficiency of the use of existing natural energy resources; promote the sustainable use of biomass resources; strengthen government capacity and streamline administrative procedures within	Technical support

		the energy sector.	
Mozambique	National Biofuels Policy and Strategy	Production of biofuels for national consumption and exports; increasing access to energy for the rural poor	Financing support
Tanzania	National Biofuels Strategy and Guidelines	Improve energy security; reduce oil imports and foreign exchange burdens; provide alternative markets for farmers; create new jobs and income generation opportunities	Technical support and capacity building
Zambia	Energy Strategy 2009-2030	Energy security; stabilise prices of transport fuels; increase investment in the agricultural sector; contribute to socio-economic development	Financial and fiscal instruments for stimulating production and use of biomass, public awareness campaigns, and the development of policies and a regulatory framework for biomass.

Annexure D:

Types of Agricultural Policies and Regulations Used by Countries

Source: Global Methane Initiative (GMI, 2014)

Country	Comprehensive Agriculture Regulations	Air Emissions from Farms	Water Emissions	Manure Storage	Nutrient Management
Belgium	✓	✓	✓	✓	✓
Bulgaria	✓	✓	✓	✓	✓
Canada	✓	✓	✓	✓	✓
China	✓	✓	✓		
Finland	✓	✓	✓	✓	✓
France	✓	✓	✓	✓	✓
Germany	✓	✓	✓	✓	✓
India	✓	✓	✓	✓	✓
Indonesia		✓			
Ireland	✓	✓	✓	✓	✓
Italy	✓	✓	✓	✓	✓
Mexico	✓	✓	✓	✓	✓
Netherlands	✓	✓	✓	✓	✓
New Zealand		✓	✓		✓
Poland	✓	✓	✓	✓	✓
South Africa		✓			
Sweden	✓	✓	✓	✓	✓
Thailand		✓	✓	✓	
United Kingdom	✓	✓	✓	✓	✓
United States	✓	✓	✓	✓	✓
Vietnam		✓	✓	✓	

Annexure E:

Policies Targets and Incentives Related to Biodigesters

Source: Global Methane Initiative (GMI, 2014)

Summary of Policies and Incentives for the 30 Countries Researched

Country	AD Policies	Renewable Energy Targets	GHG Emission Reduction Targets	AD Incentives
Argentina		■		■
Belgium	■	■	■	■
Brazil		■	■	
Bulgaria	■	■	■	■
Canada	■		■	■
Chile		■	■	
China	■	■	■	■
Dominican Republic		■	■	■
Ethiopia				■
Finland	■	■	■	■
France	■	■	■	■
Germany	■	■	■	■
India	■	■		■
Indonesia	■	■	■	■
Ireland	■	■	■	■
Italy	■	■	■	■
Mexico	■		■	■
Netherlands	■	■	■	■
New Zealand	■	■	■	■
Pakistan		■		■
Peru		■		■
Philippines				■
Poland	■		■	■
Serbia		■	■	■
South Africa	■		■	■
Sweden	■	■	■	■
Thailand	■	■	■	■
United Kingdom	■	■	■	■
United States	■	■	■	■
Vietnam	■	■	■	■