IEA Bioenergy

Technology Collaboration Programme

Decentralised Micro-biodigester Systems for rural South Africa

IEA Bioenergy: Task 36

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Decentralised Micro-biodigester Systems for rural South Africa

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Preface

This is the third of a case study compilation to explore lessons on material and energy valorisation of waste within the framework of IEA Bioenergy Task 36. The set of case studies will be published during 2021 covering social and public acceptance aspects, barriers in Waste-to-Energy (WtE) implementation, success stories for decentralized solutions, and integration of WtE within material and/or nutrient recovery. The purpose of these case studies is to showcase examples from which countries can get inspiration and support in implementing suitable policies and solutions in the waste/resource management and WtE sector that would facilitate their transition towards circularity.

IEA Bioenergy Task 36, working on the topic 'Material and Energy Valorisation of Waste in a Circular Economy', seeks to raise public awareness of sustainable energy generation from biomass residues and waste fractions including MSW as well as to increase technical information dissemination. As outlined in the 3-year work programme, Task 36 seeks to understand what role energy from waste and material recycling can have in a circular economy and identify technical and non-technical barriers and opportunities needed to achieve this vision.

See http://task36.ieabioenergy.com/ for links to the work performed by IEA Bioenergy Task 36.

Summary

South Africa's rural areas have been historically characterised by persistent service delivery challenges, including lack of waste management services, poor access to reliable sanitation systems, inconsistent and unaffordable energy options. Although the viability of biogas systems as decentralised waste management, sanitation, and energy solutions for rural areas within the Global South has been well documented within contemporary literature, biogas interventions within South Africa have not been successful for a variety of reasons, namely, limited research and implementation, despite a readily abundant supply of suitable feedstock within rural contexts.

The purpose of this report is to contribute to the development of a best practice model for rural biogas provision in South Africa. It is contextualised within two interrelated, but distinct, rural bioenergy projects located in the Ndwedwe Local Municipality (NLM), within the iLembe District Municipality in the KwaZulu-Natal Province, funded by the South African National Energy Development Institute (SANEDI) and the National Lotteries Commission (NLC). These two projects encompassed repairs to 26 existing household digesters and design and implementation of new integrated biogas provision and sanitation systems at five Early Childhood Development Centres (ECDCs). Utilising a mixed-methodological approach, interventions were evaluated on their socio-economic, energy, and sanitation outcomes, and an optimisation plan was implemented to address identified shortcomings.

What was envisaged in the Ndwedwe biogas project were answers to the following:

- What is the typical low-income/rural household's energy requirement?
- How much organic waste does the household produce?
- How much biogas could be produced?
- What reduction in deforestation does the change from the previously used fuel to biogas represent, expressed as the reduced area of deforestation and the increased carbon stock in trees?
- What is the value of the digested material as an organic fertiliser and the opportunities for valorisation thereof?
- What is the potential improvement in indoor air quality through reduced use of cook-stoves?
- Whether business opportunities could be derived for the further building, maintenance of the biogas digesters in the Ndwedwe area?
- What is the level of social acceptance of the beneficiaries to the technology and to progressively replacing LPG gas to biogas from the digesters for cooking?

While the income-level was a key consideration for the selection of households for the Ndwedwe biogas projects, other social factors, current, and in the future, were not catered for. The issue of abandonment and/or vandalization of the systems was not anticipated.

This report seeks to establish lessons learnt in the sustainability of operation and maintenance of the Ndwedwe biogas systems. The results of a detailed stakeholder engagement with municipal officials, industry, and beneficiaries, aimed at identifying barriers and drivers to implementation and rolling out of these systems, are reported hereafter.

Introduction

South Africa is seeing a large-scale shift to low-carbon energy supplies and solutions with associated changes in infrastructure requirements and the way utilities provide energy services. At the same time, the country continues the drive for universal energy access for all South Africans with particular focus on energy poverty and poverty alleviation initiatives in the country.

Biogas technology has not been very successfully promoted nor deployed in South Africa, and this is due to a number of social, political, economic and technological reasons. Amongst others, the country has a high level of electrification access and a range of subsidised free basic services. There is also an expectation that for those who do not have electricity access yet, the government will follow through with grid electrification at all costs. Government on the other hand is looking at all forms of electrification, including non-grid applications, that need to be complemented with alternative thermal and space heating technologies.
One key barrier in the successful rolling out of these systems has been identified in the lack of know-how, and lack of a structured and efficient participatory framework/platforms of the beneficiaries (the communities) that are mere unaware recipients of the technology, but do not participate in driving the development of the renewable energy sector nor in shaping climate change policy.

Experience has shown that even when rural/low-income households have been electrified, the cost of electricity is unaffordable. There is therefore an opportunity for alternative energy sources, especially for thermal applications. The biogas technology often needs high levels of skill and supervision for reliable operation and the daily labour input for its operation can be too demanding, particularly when it involves cow dung collection and mixing with water. These issues can be solved by efficient design of the biogas digester and integration of the unit into the farming/household system to require as little human intervention for operation as possible. It is estimated that in South Africa about 7 million tons of wood with a total amount of energy approximately equal to 86PJ/year is burned for heating and cooking purposes (Mukumba et al 2016)

The past decade has seen a major proliferation in the number of small-scale anaerobic, waste to energy, biogas systems, installed across several rural, and historically underserviced, South African municipalities. Designed to transform domestic waste (faecal sludge, food waste, and animal waste) into methane for cooking, one of the major selling points of these interventions, from the perspective of the state (aside from filling the obvious service provision gap), is their ability to ween beneficiaries away from the burning of other cooking fuels, in particular wood (which has to be gathered locally and contributes to deforestation), and liquid propane gas (LPG), which, though preferred by residents, is expensive and finite. From an air quality perspective, there has been significant research to show that the switch to biogas would also have significant environmental health benefits, showing clear improvements from switching from burning wood to biogas. However, these studies presume that the adoption of biogas is total and unidirectional, with beneficiaries abandoning other fuels, once the cleaner, and presumably free, biogas becomes available. Experience in South Africa, indicates however, that this is not always the case, with many beneficiaries continuing to burn a range of solid fuels, despite the availability of gas. In these contexts, why do beneficiaries continue to burn other solid fuels?

The use of a biogas digester as an integrated waste management and energy solution has been developed and promoted successfully across the Global South, particularly within Asian contexts (in China: Chen et al., 2010; Chen et al., 2017; De Clercq et al., 2017; and in India: Mittal et al., 2018; Rupnar et al., 2018; Kapoor et al., 2020). Biogas in South Africa, like many African countries, has seen only few practical applications due to a lack of investment from the state, limited domestic financial capital, and few locally available, suitable technologies (Mutungwazi et al., 2018).

Bio-digesters are conventionally utilized as part of the treatment process for faecal sludge and septage globally, for both offsite and onsite disposal (Vutai et al., 2016). However, most of these applications have been within centralised wastewater collection and treatment systems, which are costly to build and operate, especially in areas with low population densities and dispersed households, typical within rural South Africa communities. Moreover, the emphasis within such systems has been on wastewater treatment, not energy generation, therefore, although potentially usable methane gas may be created, it is often not utilised, and is just burnt off (Vutai et al., 2016). Over the past two decades, small, decentralised, bio-digesters, have increasingly been implemented within South Africa as a potential pathway for addressing energy poverty, lowering national carbon emissions, and reducing reliance on the national grid. In response, several nationally funded bio-digester projects have been developed (including within KwaZulu-Natal, Limpopo, and the Eastern Cape) which utilise locally available feedstocks (principally cow dung and food waste) to provide gas for cooking within rural households (Mutungwazi et al., 2018). However, few of these decentralised systems have attempted to utilise faecal sludge as a feedstock, and those that have, have done so in an ad-hoc fashion- leading to potentially unsanitary disposal (Ogwang et al., 2020).

Alongside with health and environmental benefits, biogas also provides social/gender benefits especially to woman and youth as they are traditionally responsible for the collection of firewood and dung (Msibi et Cornelius 2017) This is a labour-intensive work which requires a considerable amount of time depriving woman and children from the opportunity to get an education or a former training. It is renowned that lack of education is one of the main reasons of gender inequality. Research shows how biogas adoption in rural areas improves the living condition of local communities giving women and youth the opportunity to gain access to education, and to develop new skills. (Nethengwe et al 2018). Other studies on micro digesters benefits focus on the use of slurry or digestate as a nutrients-rich fertilizer.

Within this context, an integrated biogas, sanitation system, which maximises both energy and wastewater treatment outcomes would greatly contribute to local sustainability, while improving the value of state investment in green technologies.

Common typology of small digesters used in Southern Africa

Anaerobic digestion can be used to treat organic waste by reducing its chemical oxygen demand while generating biogas (a mixture of methane, carbon dioxide and trace gasses), for use as a source of energy. According to Mutungwazi et al. (2018), anaerobic digesters can be categorised, in terms of scale, as small, medium and large with a power supply capacity of less than 25 kW, between 25 and 250 kW and above 250 kW respectively, depending on the availability of feedstock.

A typical digester requires an inlet and an outlet for substrate and digestate, a headspace for the gas produced during the anaerobic digestion to be stored inside the reactor and a gas outlet to release the produced gas. The three most common typologies of small-scale or household/domestic digesters globally include the floating drum digester, the Chinese Fixed Dome Digester (CFDD) and plug flow reactors.

The CFDD is the most popular in South Africa, including within state-sponsored biogas interventions. This preference has been based on a number of characteristics marking the CFDD as suitable for rural contexts, including: its long lifespan, local availability of construction materials (when necessary), cost of construction, ease of operation, low cost of maintenance, feasibility of insulation, and general reliability.

Table 1: Limiting conditions, advantages and disadvantages of small CFD (Chinese Fixed Dome) Digesters.

Limiting conditions	Advantages	Disadvantages
• Long HRTs (hydraulic retention time) • Low influent TS (total solids) • Limited mixing • Lack of additional heating • OLR = 0.75 kgVS/m^3/day	• Relatively cheap, approximately two thirds the cost of the floating drum • Durable with relatively long life of approximately 20 years • No steel parts that may corrode • Underground construction • No mixing elements	• Difficult to construct on bedrock • Require highly skilled labour with experience in brick laying so that the overall construction is air-tight • Prone to failure due to cracking during cement curing and/or differential settlement of the structure • Gas pressure fluctuations • Prone to temperature variations • Limiting conditions influence the OLR (Organic Loading Rate) • Prone to overloading • Uneven biogas production and system failure

Moreover, the CFDD forms the basis for most prefabricated digester designs applied and commercially available within South Africa. In the CFDD design, waste enters through the inlet tank and is channelled down to the reactor chamber through an inlet pipe. As gas is produced in the reactor chamber, it is stored in a gasholder and exerts pressure on the substrate such that it is displaced into the inlet and outlet chamber, thus providing pressure to the gas which is dependent on the level of displaced substrate in the outlet and inlet chamber.

As shown in Fig. 1, the CFDD includes: inlet tank (1), inlet pipe (2) expansion chamber tank (3), gasholder (4), gas pipe (5), entry hatch (6), with gastight seal (7), reactor chamber (8), outlet pipe (9) and supernatant scum (10). As more substrate is fed into the digester, digested substrate exits through the outlet chamber which is at a lower level than the inlet. Typically, CFDD designs are dependent on the ambient or ground temperature (if installed underground) for insulation, and they have been characterised by limited internal agitation. Within rural contexts, these digesters are, in most cases, operated at long hydraulic retention times (HRTs) and low influent total solid (%TS) content, attributed to lack of heating and limited mixing. As such, they are limited to low organic loading rates (OLR) such as 0.75 kgVS/m^3/day past which they are prone to overloading which can compromise biogas production (Jegede et al, 2019 a,b; Ogwang et al., 2020).

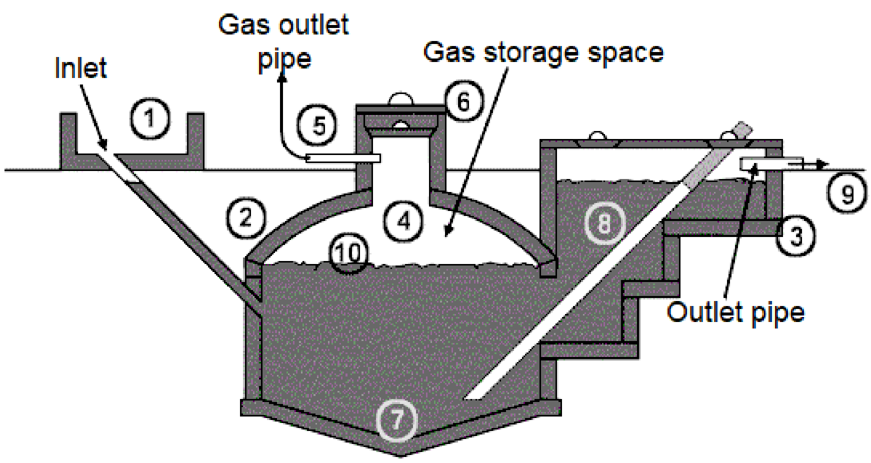

Figure 1: Typical Fixed-Dome type of small biogas digester(Cheng et al., 2014).

Case study area: The Ndwedwe local municipality

This report summarizes the work performed from 2019 to 2020 at the Ndwedwe Local Municipality (NLM), in the province of KwaZulu-Natal, in South Africa, for the refurbishment and optimization of existing household micro-digesters and installation of new institutional micro-digesters at local creches. This project, funded by the “National Lotteries Commission” (NLC) and SANEDI[1] (Working for Energy Programme)[2], was coordinated by the SARCHI Chair Waste and Climate Change at the University of KwaZulu-Natal (UKZN) and implemented by Khanyisa Projects Pty Ltd.

The two main aims of the project were:

- the refurbishment and optimization of 26 (household) micro-digesters installed by SANEDI’s Working for Energy Programme in 2016;
- the installation of 5 (institutional) micro-biodigesters, ablution blocks and rainwater harvesting tanks at Early Childhood Development Centres (ECDCs) in NLM, to manage septage, food waste and grey water in a sanitary manner. Nutrient rich effluent from the systems is safely channelled to adjacent gardens to support plant growth.

Overall, the main objectives of the project were the reduction in greenhouse gas emissions, improvement to beneficiaries’ quality of life, skills development, and the increase in biogas awareness.

There are 278 municipalities in South Africa, of which 8 metropolitans, 44 district and 226 are local municipalities. None of the municipalities in KZN apply separated collection or have fully established Material Recovery Facilities for recycling or organic waste treatment. Ndwedwe is a large rural municipality of approximately 1093 km^2 within the iLembe District Municipality in the KwaZulu-Natal (KZN) Province of South Africa. It is found approximately 20 km inland of the eastern coastline. Ndwedwe Local Municipality has a population of about 140,000 people, 70% of the population has access to electricity for lighting, while about 4% of the households have a flush toilet connected to a sewer system. According to the Ndwedwe Integrated Development Plan (2018), it is estimated that 66% of the households in the area still lack access to potable water, as a result of poor maintenance or depletion of the water source. The area is significantly underdeveloped with families commonly dependant on government grants and subsistence farming.

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[1] The South African National Energy Development Institute (SANEDI) is established as a juristic person in terms of Chapter 4 of the National Energy Act, Act 34 of 2008 with key focus areas as stipulated in the Act being energy research and development and energy efficiency.

[2] The SANEDI Working for Energy Programme was a social programme initiated in 2008/2009 with the aim of providing energy services, obtained from renewable sources, to rural and low income households. In the past 10 years, SANEDI has implemented a number of micro-digesters installations in rural areas of the KwaZulu-Natal, Limpopo, Mpumalanga and Eastern Cape Provinces of South Africa (SANEDI, 2021)

Figure 2: iLembe District Municipality, with the four local Municipalities in the insert.

Waste sources and logistics

An investigation into the available feedstock, in the Ndwedwe area, for the five ECDCs and the households was performed to assess available quantity, respective quality (biochemical characteristics) and potential energy yield. To perform investigations on the substrates, it was important to obtain representative samples of the available feedstock that could be utilised. Qualitative interviews as well as literature were used to derive the available forms of organic waste that could be used for anaerobic digestion from the selected sites.

With respect to the 26 households, it was ascertained through interviews that the existing household digesters were fed mainly with cow dung (CD), food waste (FW) and, at two of the households, with sewage from toilet connections. The locally available feedstock for the ECDCs included: human excreta, food waste and cow dung from neighbouring sources.

The population at each ECDC governs the amount of human excreta and food waste generated. Therefore, the quantity of human excreta and food waste was generated using the average amount produced by each pupil and this was multiplied by the average attendance each day. It was not possible to quantify cow dung, but desirable numbers of cows were observed in close proximity to all the ECDCs. The quantity of food waste was estimated by instructing the personnel to weigh the amount of food waste generated each day, over a number of days, and noting the respective daily student attendance.

Characterisation tests were performed on the substrates that were investigated. This information was used to optimise the process of anaerobic digestion at the respective sites. Optimisation enabled recommendations for feeding regimens, options for the digestate's disposal and operational conditions. The results from the characterisation tests with respect to each substrate tested are shown below in Tables 2 and 3.

Site selection and community engagement

The stakeholder engagement for both household digesters refurbishment and new installations at the creches was conducted by an independent NGO named Khanyisa Projects during the course of 2019 and 2020.

Municipal officials at NLM were contacted telephonically to request permission to visit and select sites for the proposed project.

All the 26 households featuring the micro-digesters were visited and the beneficiaries interviewed during the course of 2019.

For the ECDCs, possible sites were selected with the permission and assistance from ward counsellors who are in charge of the wards at NLM. Each site was visited and assessed physically to obtain relevant information. Information that could not be attained physically was obtained by use of interviews. The following criteria was used to select sites:

- **Availability of feedstock**: the primary source of feedstock was faecal sludge and food waste generated by the users of the ECDCs as well as cow dung from the surrounding areas. The quantification of food waste and human excreta was performed using population data and average attendance data. The quality of all feedstocks was investigated using laboratory tests.
- **Availability of water:** Water is important for anaerobic digesters and therefore it was important to identify or provide reliable water sources for each ECDC. This was investigated physically at the sites.
- **Presence of food gardens:** The presence of such gardens was also considered so that the digestate and/or nutrient rich effluent generated could be of value as a fertilizer for the gardens if any were present
- **Management capability**: Lastly, one of the major causes of anaerobic digester failures is the maintenance of the systems. Therefore, the management at each ECDC was qualitatively assessed to show their willingness to participate in the operation and maintenance of the digester systems.

Eight possible sites were visited and investigated according to the selected criteria such as availability of water, type of toilets, presence of a garden/orchard; availability of an onsite kitchen; available feedstock and management capacity.

The suitability of the feedstock was assessed as part of Ogwang, 2020 and detailed in Tables 2 and 3 below.

Table 2: Quality parameters for various feedstocks tested.

Sample	TS (%)	VS (%)	BOD (mg/L)	RI7 (mgO_2/gDM)	COD (mg/L)	C/N	VFA/TA
CD (SOLID)	25.23 ±0.11	88.03 ±1.03	N/A	246.41 ±10.98	35,916 ±3091.61	30.86:1	N/A
FW (SOLID)	23.93 ±0.32	95.46 ±0.43	N/A	175.62 ±12.67	100,921 ±9052.21	26.48:1	0.8
HE (SOLID)	8.47 ±0.69	83.07 ±0.41	N/A	704.34 ±21.04	95,867 ±8632.21	5.88:1	N/A
DG1 (LIQUID)	1.56 ±0.78	26.33 ±0.56	607.33 ±54.69	N/A	18,724 ±1523.21	14.26:1	N/A
DG2 (LIQUID)	5.60 ±1.60	36.39 ±0.40	1798.33 ±167.17	N/A	18,670 ±1453.32	N/A	N/A
IN (LIQUID)	3.26 ±0.11	74.77 ±0.86	311.67 (±21.57)	N/A	21,640 (±1856.32)	12.40:1	N/A

CD: Cow Dung; FW: Food Waste; HE: Human excreta; DG: Digestate; IN: Influent

TS: total solid; VS: volatile solids; BOD: biological oxygen demand; RI7: respiration index at 7days; COD: chemical oxygen demand; VFA/TA: ratio volatile fatty acid to total alkalinity

Anaerobic digestion can be efficient at pathogen reductions. A detailed account of the pathogen counts and impact of the digestate samples against the inlet feedstock was conducted and reported in Table 3, with the aim to assess the suitability of the feedstock, the absence of toxic elements, the effectiveness of the digestion progress at optimal conditions and, finally, the suitability of the digestate as a soil amendant. The digestate from the household digesters at NLM is disposed on land without any use of soakaways. An important optimisation adopted in the institutional micro-digesters at the creches was the installation of ad hoc soakaways or reed beds, to reduce the pathogenic impact of the digestates and its efficient reuse for irrigation. These decisions were informed by the results in Table 3.

Table 3: Pathogen counts for various feedstocks tested in CFU/g-Solids or CFU/mg-Liquids

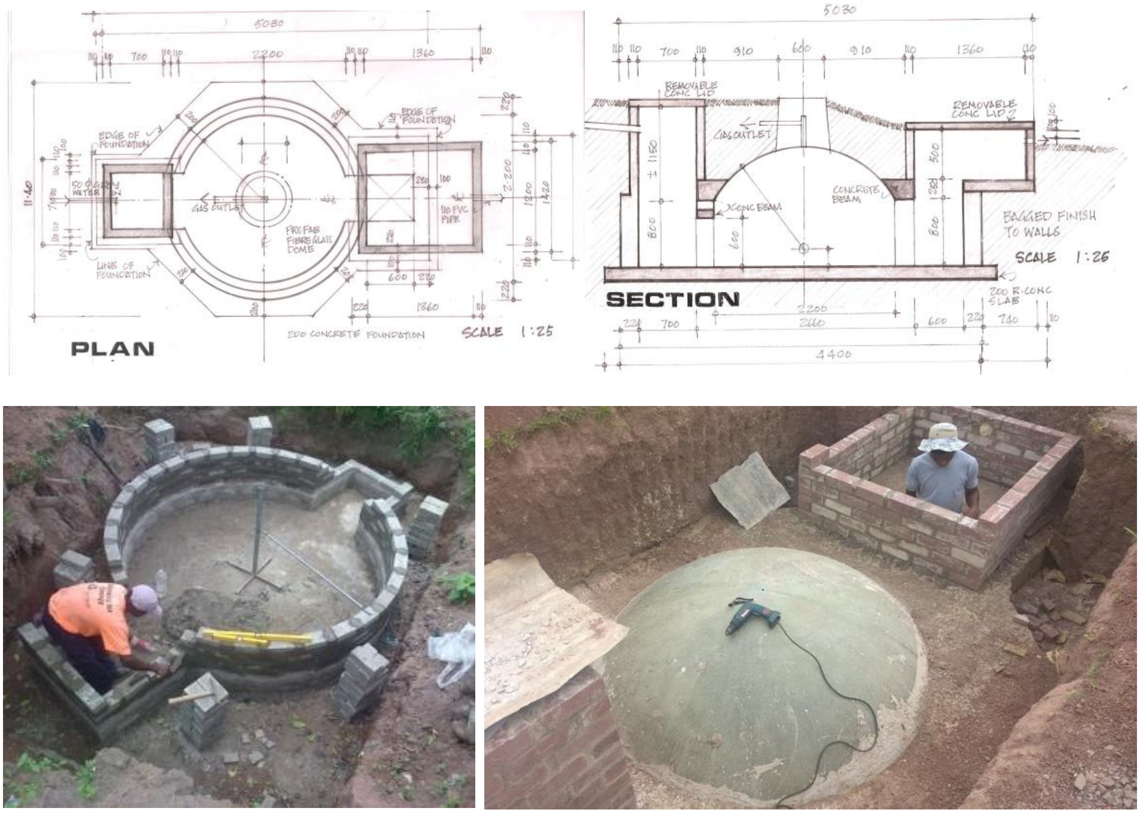
Sample	E.Coli	Faecal Coliforms	Faecal Streptococci	Enterococci
CD (SOLID)	16,600	N/A	1100	6,000
FW (SOLID)	<10	N/A	92,000	149,000
HE (SOLID)	21,600	N/A	130,000	250,000
DG1 (LIQUID)	2,000,000	2,000,000	12,000	150
DG2 (LIQUID)	27,000	180,000	180,000	220
IN (LIQUID)	3,600,000	18,000,000	10,000	110
CD: Cow Dung; FW: Food Waste; HE: Human excreta; DG: Digestate; IN: Influent				

Technical Implementation

HOUSEHOLD DIGESTERS

The anaerobic digester typology used at the 26 rural households is a brick-and-mortar Chinese Fixed Dome Digester (CFDD) within a moulded fibre glass dome, and a solar lighting system at each house. Figures 3a and 3b show the original design drawings of the digesters used at the NLM households as well as some photos during the construction phase.

Construction was undertaken through purposely trained local building crews. The key milestone dates for the original programme were the completion of all construction by the end of the 11th month from beginning of the installation. While the completion of the aftercare phase by the end of the 13th month. The construction of all 26 digesters was completed as scheduled, however, the addition of rainwater harvesting systems in each house resulted in the Aftercare and Evaluation being extended by several months.



Figures 3a and 3b: 3a (top) - Plan and section of the biodigesters installed at Ndwedwe; 3b (bottom) - Photos during the installation of the household digesters. Design and photos courtesy of Khanyisa Projects and SANEDI (Khanyisa Projects, 2014)

During the course of 2019, the UKZN team underwent a refurbishment and optimisation campaign of the SANEDI digesters at Ndwedwe. Some of the key points and lessons learnt from this exercise informed an optimised process layout and design and installation of the institutional digesters at the five ECDCs, as presented in Figure 4 and detailed below.

Key points and observations that informed the design of the institutional micro-digesters at the creches in 2019:

- Gas pipelines were installed with a downward slope to prevent condensed water from getting trapped in the gas pipelines. In addition, a new robust type of gas-line pipe was used instead of the previously used PVC pipes as shown in Figure 4. This pipe is made up of a longitudinal butt-welded aluminium layer that is surrounded on the inside and outside by layers of cross-linked polyethylene. The inner and outer PEX layers inhibit scaling and corrosion while the aluminium provides it with strength. Furthermore, this new type of pipe is easier to install and cheaper than the previously used PVC pipe. Furthermore, a new design to prevent condensate water within the pipeline was designed as shown in Figure 4. The design enables water to remain trapped and removed at the point of lowest depression by means of a water trap that is constructed using a valve and pipe extension.

However, given, the socio-cultural context, and the burden on beneficiaries of regularly emptying the water trap, this should only be considered a temporary solution.

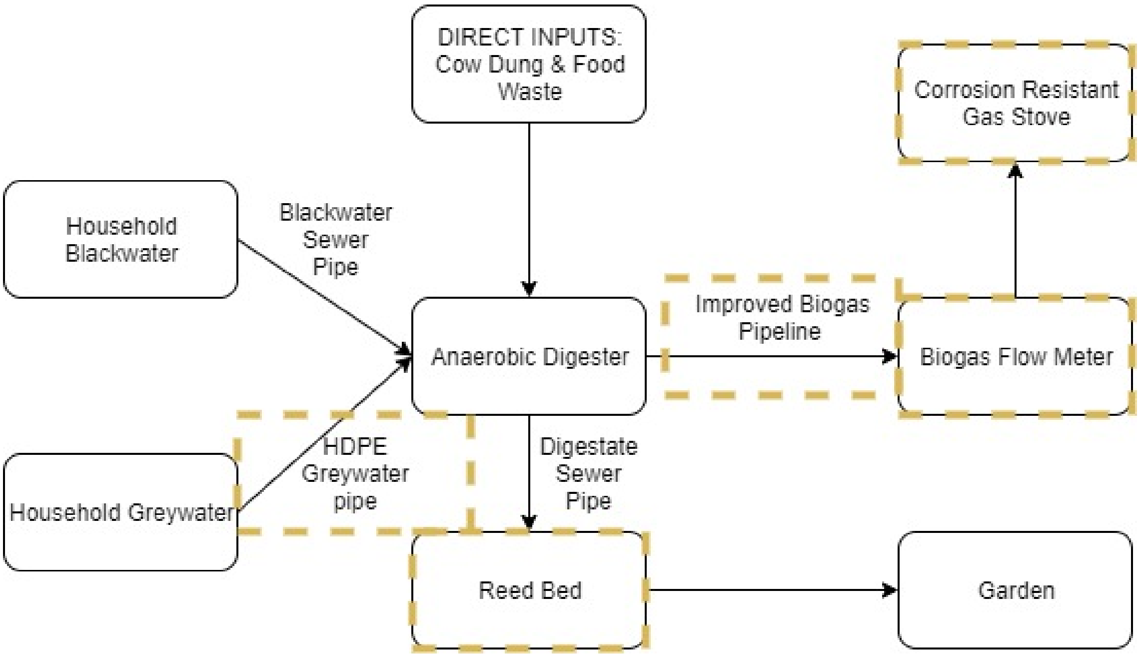


Figure 4: Optimised household digestion process system flow chart (yellow represents additions to the original process design)

- A best attempt was made to obtain a ceramic burner stove but it was not possible to obtain one within the project timeline. Therefore, a stainless steel, cast aluminium, ceramic head stove with a less rust susceptible burner was installed.
- The concentrations of H_2S in the biogas becomes potentially harmful when above 50 ppm. The smell of H_2S is also used to identify gas leaks, so therefore, in this rural context, hydrogensulfide scrubbers were not installed. Moreover, the H_2S contributes to corrosion and the rapid degradation of the metal components of the system, in particular, the cook stove. H_2S scrubbers that were available would need replacement and specialised suppliers would be difficult to find in the area. Wet steel wool scrubbers would be effective at removing H_2S from the gas, however, they would require frequent replacement, which, given the context, would likely be unfeasible.
- All toilets within the households were connected to the digester, if possible, to provide a sanitation service. Additionally, soakaways were installed at each household to enable a sanitary disposal of the digestate.
- A pressure meter was added to enable monitoring of available gas quantities. However, this may not be a mandatory additional component unless feedstock is limited.
- Lastly, the greywater pipes that were used previously were made of LDPE and were prone to damage from farm tools. Therefore, HDPE pipes were used because they are stronger and were actually cheaper in cost.

INSTITUTIONAL DIGESTERS AT THE CRECHES

The results from the investigation on the feasibility of the 26 household digesters suggest that the current design of bio-digester built by SANEDI in NLM is largely successful at producing viable gas with locally available feedstock, however persistent infrastructural issues related to the delivery of gas to the home, as well as a number of socio-cultural factors, severely impacted the success of the interventions.

The systems designed for the ECDCs comprised of technical components that had to be carefully selected. These components include: the anaerobic digester, toilets, gas-lines, pipelines. The optimisations proposed for the 26 households have been applied to the ECDCs.

Considerations were made to design and implement an optimised anaerobic digester made of brick-and-mortar. However, this was hindered by the timeline of the project. The most suitable anaerobic digester for the sites had to meet the following criteria:

- Long Lifespan: A long lifespan is governed by the structural integrity of the digester. Structural integrity is governed by the type of section and material used to design the digester. Therefore, the structural integrity of the available digesters was critically evaluated as part of the selection criteria for the most suitable digester.
- Relatively easy installation: The project was restricted by a specific timeline and therefore it was important to select a digester that would be easily installed in the shortest possible time.
- Very simple to operate and maintain: The intended users of the biogas had no experience with anaerobic digesters. Evidence of this is shown by the associated failures in the biogas systems used by the rural households. Therefore, it was important to select a digester that would be simple to operate and maintain.
- Must be able to be installed underground: The selected digester had to be installed underground in order to maximise the insulative nature of the ground since no additional heating would be considered. As mentioned earlier, additional heating requires technology which would require additional maintenance and yet one of the goals to be met was little or no maintenance requirements.
- Optimal performance: Lastly, the selected digester would need to perform optimally and remain stable with respect to the feedstock available.

Therefore, after a careful review of the available domestic digester designs in South Africa, the “AGAMA Biogas Pro” 6 m^3 (AGBP6) digester (see Figure 5) was selected for all the ECDCs. Despite the small population size at the “Babunene” ECDC, a 6 m^3 digester was still selected for the site due to inability to obtain a suitable smaller sized digester. The digester was selected as it best met the required criteria.

The AGBP6 is a 6 m^3 digester with a self-contained gas storage chamber of about 2 m^3 as well as a 2 m^3 expansion volume. It is a prefabricated digester, that can be easily installed and has a lower risk of cracks provided it is handled carefully. It is designed with its expansion chamber at the top of the digester; this enables pressure provision to the generated biogas. The digester structure is made of LLDPE (linear-low density polyethylene) which has been deliberately overdesigned with extra thick wall. The ribbed structure enables it to better withstand ground forces as the load is reduced across the surface area of the structure. Therefore, it is expected to have a long lifespan. The digester’s inlet sewer pipe will be attached to a “T-fitting” with a pipe that extends to the bottom of the digester (Figure 4-26). This reduces “short circuiting” by influent sewage. It will also reduce odours due to human excreta as one opens the inlet to feed the digester.

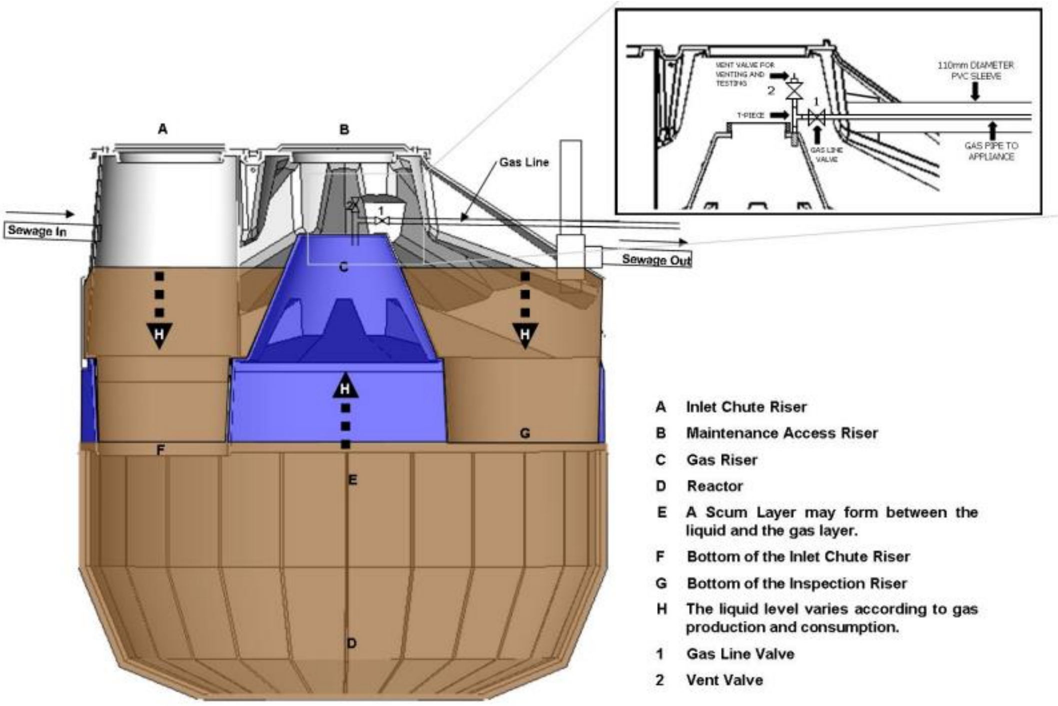


Figure 5: Vertical cross-section through ABP6. (Source: Agama Biogas Pro).

The “AGAMA” 6 m^3 digester was priced at approximately 35,000 ZAR (1 900 EUROs) and offered at a 15 % discount. A bio-bag-type digester was priced less; however, it was deemed unsuitable for the site due to its susceptibility to damage, especially at an ECDC. Lastly the AGBP6 does not have any moving or rusting parts and therefore will require low maintenance.

The toilet system acts as a user interface as well as source of, feedstock (human excreta), and water (flush water). Toilet systems can be either dry or wet systems which differ in that the latter require water for operation. In the case of the systems at the ECDCs that required toilets, a wet system was necessary due to an anaerobic digester’s water requirements. Only one of the ECDCs had a wet toilet system and therefore it was left intact and connected to the rest of the system.

A pour flush toilet and a water closet are the two types of wet toilet systems available in rural areas of South Africa. The main difference between a pour flush and a water closet user interface is the difference in water usage (a pour flush toilet uses 2 litres of water per flush while a water closet uses between 5 to 9 litres). In order to promote optimal performance of the digester and to conserve water, a pour flush toilet was selected to be used at the ECDCs where it was required.

An imperative component to the overall system was a water supply system to the toilets and hence the digester system. Rainwater tanks were present at each of the sites that required water supply interventions; however, they were not at favourable proximity to the toilet systems. Therefore, additional rainwater tanks were installed and were linked using robust HDPE pipe. The tanks were linked such that they were able to fill simultaneously with the already present rainwater tanks which are supplied with water from a yard tap or a municipal truck.

Ancillary components that were considered included the water supply components, gas, greywater, and sewer pipes as well as the gas stove, and other accessories. All components of the system have been carefully selected to have a long lifespan, low maintenance and optimal performance. Inside each creche, a pressure meter, sulphur trap and flow meter have been installed. The pressure meter provides an indication of how much gas is left in the digester. The sulphur traps were installed to reduce hydrogen sulphide within the biogas. Flow meters provide an indication of how much gas is used; they are an important component for compliance with the (National Energy Regulator South Africa) NERSA regulations. Gas-lines were raised along the kitchen walls to mitigate condensate water and water traps were installed at the lowest point just before the gasoline rises up.

Economical aspects of the installation

The expenditure on the repairs done at the households was negligible as the main objective was to identify pitfalls that may be alleviated in future projects. These optimisations were applied to the five ECDCs and Table 4 below shows the expenditure at each site.

Table 4: Costs for purchasing and installation of the micro-digesters at the ECDCs.

Sample	COST (R)	COST (EURO)
Vukuzenzile Crèche	R82 337.54	4761.61
Ukuhlalanathi Crèche	R140 571.04	8129.28
Sphumelele Crèche	R118 105.78	6830.10
Siyaqhubela Crèche	R106 531.08	6160.73
Babunene Crèche	R120 765.98	6983.94
SUB TOTAL	**R568 311.42**	**32865.66**
Contingencies (5%)	R28 415.57	1643.28
TOTAL	**R596 726.99**	**34508.95**

Sample	COST (R)	COST (EURO)
VAT (15%)	R89 509.05	5176.34
NETT TOTAL	**R686 236.04**	**39685.29**

Table 5 below shows the minimum cooking time that could be provided at each ECDC based on the minimum available quantities of waste.

Table 5: Operating conditions, estimated biogas yields and available cooking hours per day at the ECDC

ECDC	Avg. daily attendance	Avg. stool weight (Kg)	Avg. Urine Vol. (L)	Water Used Per Flush (L)	Water per Hand Wash (L)	Avg. Food Waste per day (Kg)	Solids Flow Rate (Kg/day)	Liquid Flow Rate (L/day)	Biogas Yield (HE m^3)	Biogas Yield (FW m^3)	Total Biogas (m^3)	Cooking Hours
Ukuhlananthi	130	11.05	104	260	39	5	16.05	403	0.807	0.638	1.445	1.806
Vukuzenzele	37	3.145	29.6	74	11.1	1.423	4.568	114.7	0.229	0.181	0.411	0.514
Babunene	19	1.615	15.2	38	5.7	0.730	2.345	58.9	0.117	0.093	0.211	0.264
Sphumelele	50	4.25	40	100	15	1.923	6.173	155	0.310	0.245	0.555	0.694
Siyaqhubheka	100	8.5	80	200	30	3.846	12.346	310	0.620	0.491	1.111	1.389

Environmental Aspects of the installation

The effluent from the digester systems undergoes post anaerobic and anoxic treatment in a septic tank[3] and through a drain-field which allows the nutrient-rich effluent to percolate into adjacent gardens using a soakaway or a reed bed.

Both were constructed one metre below ground level to take advantage of the aerobic zone which occurs at this depth below ground. The filtration gravel media will also facilitate further pathogen reduction. The effluent would provide nutrients to the plants which also aid in the treatment process. The soakaways were designed and installed using recycled tyres wrapped in a geo-synthetic material. It is an example of adding value to a waste product (waste tyres) and it reduces costs. The soakaway was only utilised at one of the sites and banana trees would be planted around the soakaway. This was done to provide extra treatment capacity and would enable comparison of the two treatment processes for UKZN's research purposes.

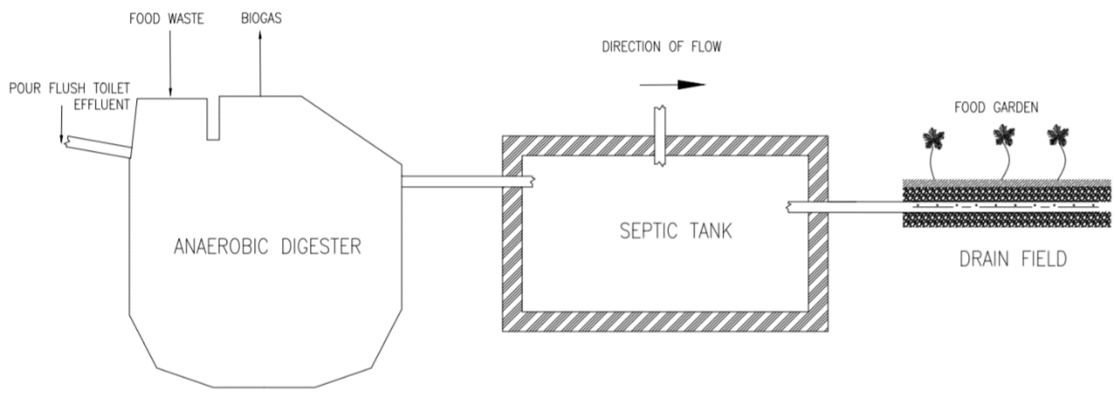


Figure 6: Layout of anaerobic digester and draining systems used at the ECDCs.

Apart from the methane gas at 60 % Vol CH_4/Vol Air, other by-products include: (i) Nutrient rich effluent; (ii) Solid digestate and (iii)Waste heat.

All stakeholders interviewed agreed on the significant number of environmental and health benefits associated with micro digesters preventing air and water pollution and promoting waste management and healthier living conditions. The installation of bio-gas digesters was said to be relieving pressure on the use of natural resources (wood) for energy production for cooking. Some stakeholders highlighted how a limited number of hazards and health risks associated with biogas micro-digesters where balanced by many benefits especially when the digesters are correctly managed and operated (Reale, 2021).

[3] Not all ECDCs possess a septic tank following the digester.

Lessons learnt and recommendations

Despite the efforts and the implementation of a number of micro digesters as pilot projects in different provinces across the country, biogas technology in rural areas has seen a limited uptake. Some of the reasons for this limited uptake could be attributed to the cost of the micro digesters, the accessibility of remote rural areas in the countryside and especially the lack of information and understanding on biogas, which have prevented the demand of biogas technology among local communities. The following section explores the lessons learnt in the optimisation of the household digesters and the installation of the 5 EDCDs' digesters at NLM.

CONSIDERATIONS ON THE HOUSEHOLD MICRO-DIGESTERS

Over the five-year period, twenty out of the 26 digesters were still producing gas and out of the six dysfunctional ones, one had a structural failure, and one had a burnt dome. The other four anaerobic digesters were not functioning due to damaged or removed dome valves, which are difficult to repair or replace. This shows that if a digester is installed and maintained correctly, it will have a long lifespan. To improve probability of airtightness, one should use a waterproofing admixture to the mortar mix used for its construction. Installation should also be done carefully to prevent settlement of the slab below the digester structure which causes leaks.

It can be concluded that the fixed dome digester can be suitable for a rural setting especially if a prefabricated dome is used, as it eases construction and reduces the risk of leaks at the dome. Education to users about maintenance can improve the success rate of these digester-types.

Despite the advantages of the technology, the high cost of installation and long pay-back periods can be unfavourable for rural households which are associated with low income.

The study finds that the issues that have hindered the successful implementation of biogas interventions in rural areas are manifold but can be eliminated or optimised to produce better waste management, sanitation, or energy outcomes. Optimisations were proposed to address the identified shortcomings to improve success and long-term sustainability. An optimised process flow chart for the households was developed. Within the optimised household digestion process system: 1) all toilets were to be connected to the digester, where necessary, to treat human excreta, 2) all system components were replaced with more sustainable components that is to say; robust long lasting HDPE grey water pipes, corrosion resistant stoves and an improved biogas pipeline 3) A biogas flow meter was added to indicate available biogas quantity (may only be added if financially viable and feedstock is limited) and finally 4) soakaways to enable sanitary disposal of digestate.

A number of factors unique to the local context of Ndwedwe impacted the rehabilitation works. One of these, and a feature of rural life in South Africa, is the fluidity of rural households. Between implementation and the rehabilitation, two of the 26 households had been abandoned. Moreover, at many of the households, the household head was no longer resident, and in many instances, the new household had not been living there at the time of the digester installation and training. This household fluidity greater hindered the development of beneficiary knowledge and memory regarding care and maintenance of the systems. One advantage of prefabricated digesters, as opposed to "brick and mortar" systems, is that they could be reclaimed and reinstalled elsewhere if abandoned or neglected.

Another contextual factor that impacted work was persistent water scarcity through the study area. None of the beneficiary houses have piped water, and most rely on municipal water truck deliveries. Most still have the rainwater harvesting systems installed by SANEDI-Khanyisa Projects, but many are in poor repair, and still, rarely get a household through drier periods of the year. This persistent water scarcity at work sites necessitated making alternative plans when water was required for construction work. This included hiring a water pump, to pump water from the uMlodti River to fill the rehabilitated digester, as well as to carry water daily with the rehabilitation team for everyday needs, so as to not place an unnecessary burden on beneficiaries. The connection of grey water gullies to the digesters was one solution that Khanyisa Projects implemented to get water to the digester, however, integrated sanitation biogas systems, using poor flush toilets have suggested more positive outcomes related to water conservation at the ECDCs sites.

One service that has improved since the commissioning of the digesters, however, is access to electricity. In 2013 few of the beneficiaries had electricity, however, in 2019, nearly all do. However, few can afford to utilise it for more than basic lighting, and most continue to cook with combustible fuel sources. This is seemingly due to a variety of factors, such as convenience, choice, and the poor performance of many of the biogas systems.

These suggested improvements in design and implementation should inform future biogas interventions in KwaZulu-Natal, while contributing to a best practice model for rural biogas provision in South Africa.

CONSIDERATIONS ON THE ECDCS MICRO-DIGESTERS

The solutions designed for the ECDCs represent an optimised anaerobic digestion process which also functions as a sanitation system. All components of the system have been carefully selected to have a long lifespan, low maintenance and optimal performance. The results from the characterisation tests show that anaerobic digesters reduce COD and pathogens, and an even higher removal efficiency will be expected when coupled with a septic tank. Furthermore, a safe disposal system has been designed to prevent any possibilities of pollution caused by residual untreated pathogens.

A final contextual issue that manifested during the investigation were persistent issues related to corrosion and maintenance with the cast iron stoves provided to beneficiaries. These cast iron stoves were originally designed for LPG and were modified by drilling the jet using a 2mm drill bit. During the maintenance and investigation of the 26 household digester systems, none of these stoves were found to be functioning. The reasons for this include: clogging of burners with rust and faulty components such as manifolds and valves. Routine maintenance is a consistent issue across the board, and no system could be said to have been well looked after by the beneficiary. Therefore, improving the beneficiary's knowledge of the systems, via ad hoc training, is imperative towards building capacity to conduct routine maintenance.

A stainless-steel stove was purchased to replace the currently used cast iron stoves at the households. Similarly, the jets were drilled using a 2mm drill bit. The stoves, themselves, have not failed since implementation at the households. Both stoves however have not been designed for biogas and therefore, the air to biogas ratio is not known and its effects have not been established. There remains significant opportunity to develop a purpose-built biogas stove for the South African market, and UKZN has partnered with Defy Appliances (Subsidiary of Arcelik Incorporated) towards developing fit-for purpose gas appliances for the African market.

Institutional drivers and barriers

In recent years, the South African Government and other stakeholders have tried to leverage on biogas micro-digesters technology to promote social economic development in rural areas. However, biogas technology has not been very successfully promoted nor deployed in South Africa, due to a number of social, political, economic, and technological factors. A general lack of awareness and information about biogas technology and waste management policies, a lack of cooperation among government national and provincial departments, the inadequacy of stakeholder's engagement process and the lack of financial resources and incentives to develop biogas projects in rural areas, have prevented the penetration of the technology which is still at its infancy.

A number of institutional barriers were identified as part of a research project conducted at UKZN in 2021 (Reale, 2021) that engaged stakeholders from national and municipal governments, as well as officials from SANEDI, from industry and from academia. The barriers identified were:

- technologies barriers;
- market barriers;
- social and cultural barriers;
- regulatory and institutional barriers;
- technical and infrastructural barriers;
- information barriers.

The dissemination of the biogas technology on a wide scale remains a difficult challenge in South Africa as a clear policy on biogas technology implementation is largely absent and is not part of the government's policy agenda. The lack of a clear regulation on renewable energy in general and biogas micro digesters, in particular, have contributed, together with other factors, to an interruption of the implementation of the micro digester projects within NLM.

Therefore, development of a nationwide awareness campaign on biogas is critical to disseminate information about biogas technology and its benefits amongst local communities. Hence, independent agencies, such as SABIA, GIZ, SAGEN and other stakeholders of the biogas industry in South Africa, could play a very important role to lobby for the implementation of the biogas agenda especially in connection with sharing information and awareness (Reale, 2021).

In summary the main factors driving and hampering the acceleration towards biogas technology development and implementation in South Africa are reported in Table 6.

Table 6: Institutional drivers and barriers for the rolling out of micro-digesters in South Africa (Reale, 2021)

Drivers	Barriers
• Regulatory framework promoting renewable energy • Green funding and incentives • Energy water and food security nexus • Availability of feedstock sources • Government's commitment to cleaner energy sources • Awareness and information campaign on biogas	• Lack of enforcement of the rule of law and compliance • Lack of implementation of current legislation • Lack of cooperation among government national and provincial departments • No definition of small biogas projects • Political conservatism • Industry fragmentation

Technology acceptance and awareness

The negative perception of biogas micro-digesters largely due to poor technology performance, makes stakeholders and beneficiaries hesitant towards the development of biogas micro digesters. Stakeholders at NLM have highlighted opportunities that biogas technology provides for resource use and optimization at various levels, considering the synergies of water provision, energy security and resource efficiency that the system can provide

One critical challenge on the upscaling of the systems have been identified in the lack of awareness and participation of the communities that are the direct beneficiaries of the project. The NLM was the recipient, between 2013 and 2014, of a waste to energy biogas systems, solar lighting, and rainwater harvesting tanks with the main objectives to reduce greenhouse gas emissions, to improve the beneficiaries' quality of life, promote skills development, and to increase biogas awareness. (Reale, 2021)

Market barriers

The limited implementation of biogas technology has prevented local communities to familiarize with the technology and to benefits from it. Additionally, the limited growth of biogas micro digesters industry has stopped potential stakeholders and entrepreneurs to invest on biogas technology. Despite the implementation of 26 household micro digesters and 5 in ECDC, the majority of the households in NLM still have no knowledge or understanding on biogas micro-digesters in terms of technology and benefits.

Social-economic barriers and benefits

The stakeholders interviewed concorded in highlighting the was the socio-economic benefits associated with the implementation of micro-digesters which seems to be numerous and variable ranging from:

- _Reduction in expenses for electricity and gas,
- _Increased agricultural yields,

- _Jobs creation,
- _Alleviation of poverty,
- _Cost and time saving from firewood,
- _Increased income and employment from integrating cattle rearing and farming,
- _Time-saving for women,
- _Reduction of drudgery for women.

Beyond distributed generation, biogas can bring other benefits to low-income households in rural areas, such as clean fuel for cooking. Other stakeholders pointed out at gender equality issues related to the implementation of micro digesters in rural areas. Biogas micro digesters can empower women who every day spend hours searching for wood to cook with, may be the first beneficiaries of small biogas project as this gives them the time and the opportunity to continue with their school education or to get some former training.

Moreover, before the installation of biogas micro digesters, most of the project beneficiaries in NLM were used to buy LPG gas from local suppliers. The cost of LPG gas in South Africa is currently set at 30 ZAR per litre, although is constantly increasing. Therefore, the new prefabricated digesters in the five ECDC were providing a consistent saving on the cost of LPG and the logistic involved with its provision.

According to the ECDC local managers, Ukuhlalanathi and Siyaqubekha, the largest spent about R800 on 20 kg LPG cylinder refills twice a month while Vukuzenzele and Sphumele spent R400 on 20 kg LPG cylinder refills once a month. Babunene ECDC spent about R200 on 9kg LPG cylinder refills once a month (Ogwang 2020). It is noteworthy to mention that the savings on LPG, excludes the cost of purchasing the gas cylinder and the cost of transport for the refilling.

Besides the monetary savings from energy provision, the beneficiary of the micro digesters system, showed a positive interest in the biogas technology and other community members were also attracted by curiosity to the technology.

Furthermore, the installation of the micro digesters in the ECDC required a reliable water supply to allow the biogas system to work and to flush the toilet connected to the digesters. Only one of the five ECDC had a reliable water supply. Therefore, it was necessary to install at each site a 'JoJo' tank for the collection of rainwater. The water supply was a substantial benefit for the ECDC, as it contributed to improve sanitation and to ameliorate the living condition of all the beneficiaries.

Finally, the third objective of this study was to explore the current financial support for the development of biogas technology. The assessed benefits of micro digester system as a renewable and affordable energy source they been established by a number of research studies. However, the financial attractiveness of biogas technology investment in rural areas still need to be addressed.

The average cost of 6 m^3 micro-digesters in South Africa is between R50 000 and R60 000 (3000-4000 Euros). This cost does not include the gas stove and all the fittings which are normally purchased separately by the householders, and which cost between R500 and R6000. Most of the participants agreed that the financial accessibility for poor communities is still a great limitation for supporting a continuous growth pattern.

Table 7: Institutional barriers to micro-digesters implementation in South Africa (Reale, 2021)

Technologies barriers	Market barriers	Social barriers	Technical & infrastructural barriers	Regulator & barriers	Info. barriers
Availability of Feedstock	Lack of incentives	Human waste/food association	Lack of service provider	Lack of political support	Lack of awareness and information
Availability of Water	Lack of microfinancing	Smell of methane gas	Lack of maintenance and assistance	Conflictin g governme nt policy	Lack of engagement with local communities
Need of stable temperature and suitable climate condition	Lack of subsidies	Fear of explosion	Failed biogas micro digesters	Lack of engageme nt with the local municipali ties	Lack of education on biogas technology in schools
Lack of vehicles for feedstock transportation	Low price of fossil fuels	Lack of public participation	Lack of appliances compatible with methane gas	Lack of engageme nt with the private sector	Stigmatizatio n And cultural barriers
Low number of micro digesters	Competition with LPG	Low level of education	Poor quality of pipes and fittings.	High level of administra tion and legal	Scarcity of micro digesters
Availability of Feedstock	Lack of incentives	Human waste/food association	Lack of service provider	Lack of political support	Lack of awareness and information
Availability of Water	Lack of microfinancing	Smell of methane gas	Lack of maintenance and assistance	Conflictin g governme nt policy	Lack of engagement with local communities
Need of stable temperature and suitable climate condition	Lack of subsidies	Fear of explosion	Failed biogas micro digesters	Lack of engageme nt with the local	Lack of education on biogas technology in

Technologies barriers	Market barriers	Social barriers	Technical & infrastructural barriers	Regulator & barriers	Info. barriers
				municipalities	schools
Lack of vehicles for feedstock transportation	Low price of fossil fuels	Lack of public participation	Lack of appliances compatible with methane gas	Lack of engagement with the private sector	Stigmatization And cultural barriers

Table 8: Institutional drivers to micro-digesters implementation in South Africa (Reale, 2021)

Technologies drivers	Market drivers	Social drivers	Technical & infrastructural drivers	Regulatory drivers	Info. drivers
Efficient Waste management	Bank loans incentives	Community empowerment	New technology development for micro digesters	Clear policy definition for biogas projects	Education and training programs
Water/food /energy Nexus	Cost savings on energy	Woman empowerment	Improved fittings and pipes	Government collaboration with local Municip.	Biogas projects development in rural areas
Water sanitation	Development of new market niches (appliances)	Improved health condition	Service provider establishment	Ngo involvement and participation	Communication sharing platforms
Energy decentralization	Encourage market competition among producers	Environment preservation	Compatible appliances development	Development of more PPP projects	Awareness campaign on benefits and technology
Affordable methane gas for cooking heating and lighting	Availability of financial support for project and research on biogas	New Skills development	Prefabricated digesters are deemed the most suitable then bricks and mortar	Clear regulation for micro-digesters development	Community engagement with local stakeholders and municipaliti

Technologies drivers	Market drivers	Social drivers	Technical & infrastructural drivers	Regulatory drivers	Info. drivers
	development			in rural areas	es
Bio slurry as a fertilizer	International cooperation	Entrepreneurship	Micro digesters	Implementation of	Opportunity to develop Local
Efficient Waste management	Bank loans incentives	Community empowerment	New technology development for micro digesters	Clear policy definition for biogas projects	Education and training programs
Lack of vehicles for feedstock transportation	Low price of fossil fuels	Lack of public participation	Lack of appliances compatible with methane gas	Lack of engagement with the private sector	Stigmatization and cultural barriers

Many factors hinder the adoption of biogas micro digesters technology in South Africa. The continued use of coal and fossil fuels as an energy source is a barrier to transitioning towards more sustainable energy sources especially in rural areas. Other institutional barriers to the implementation of biogas micro digesters are politics, governance, technical, social-cultural, financial and economic, market-related, geographical and ecological factors. All these factors work together to restrict the development and adoption of micro digesters. Moreover, the political will to maintain the control of energy generation and provision at central level, has limited the deployment of renewable energy system in general and biogas technology in particular. Therefore, despite a growing sense of urgency, and despite advocacy for energy democracy, the uptakes of renewable energy systems in South Africa have been very slow (Reale, 2021).

Final Conclusions

The installation of more of 1000 micro-digesters scattered in different rural areas across South Africa, has successfully proven the potential of this technology in the provision of energy for remote rural areas. Micro digesters are providing affordable cooking gas, heating and lighting to rural communities thus supporting poverty alleviation and local economic development. According to stakeholders of the Ndwedwe biogas project, one of the possible reasons for the lack of implementation of large-scale micro digesters projects, could be attributed to the failure of the South African Government to endorse a clear biogas policy to provide guidelines, standards and promote financial incentives to encourage this potential new market sector. Nevertheless, a detailed policy analysis has shown that South Africa enjoys a comprehensive legislation on the renewable energy and waste management sectors:

the two relevant sectors linked to biogas technology. Furthermore, policy such as the White Paper, the Green Paper and others are clearly supporting the implementation of energy access. “Energy security for low-income households can help reduce poverty, increase livelihoods and improve living standards” (RSA White paper 1998).

The involvement and the participation of the whole community and the local authorities are preliminary and essential activities for the sustainable development of the project. Moreover, the consultation with all the participants is essential to create a common vision for the purpose of developing biogas micro digesters technology in local municipalities.

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- SANEDI industry support tool: refurbishment guidelines for decentralised rural micro-digester systems. (2020) Authors: Marc Kalina, Jonathan Ogwang and Cristina Trois. Presented to SANEDI in 2020.
- An investigation into biogas as an energy solution in rural South African households. Master of Engineering Dissertation, Jonathan Ogwang, 2020.
- Institutional barriers and drivers to the implementation of micro-digesters in rural areas of South Africa: a case study of the Ndwedwe municipality in Kwazulu-Natal. Master of commerce Dissertation. Gisella Reale, 2021.

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