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Is small-scale biogas production a viable source of electricity in rural Sub-Saharan Africa?

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ABSTRACT

This study investigates the benefits and limitations of small-scale biogas technology at the household level in rural Sub-Saharan Africa. A literature study and a case study were done to explore if small-scale biogas production is a viable source of electricity in rural Sub-Saharan Africa. The results show that using cattle manure as feedstock requires a daily substrate flow of 750 L of the diluted substrate, i.e. 250 kg of manure and 500 L of water for a 24-hour electricity supply, using a 2-kW generator. This requires a minimum herd size of 25 cattle. Most households don't have so many cattle. However, a herd of 10 cattle provides enough biogas to power several electrical appliances, significantly improving the household's energy situation. The study concludes that the uptake of biogas technology in Sub-Saharan Africa is slow. Common barriers include inadequate substrate supply, lack of water and variable temperatures, high initial costs, poor technical quality, intense labour operations and maintenance, and insufficient policy support. Improved uptake of biogas technology in Sub-Saharan Africa requires establishing national institutional frameworks and supporting policies, collaboration with the intended users of the technology and local support organisations, ensuring long-term local availability of spare parts and supplies, and, when household-level access to feedstock is limited, centralise biogas systems on the village level to combine feedstock into one production system.

Keywords: rural electrification, small-scale biogas digester, electricity generation, cattle manure

1. INTRODUCTION

Reliable access to energy is essential for socio-economic development and improved livelihoods [1-3]. Modern energy services are crucial to realising the UN Sustainable Development Goals (UN-SDG), specifically Goal 7: Ensure access to affordable, reliable and sustainable energy for all [4]. Many rural communities in developing countries lack modern energy access for basic cooking, lighting, and powering of low-voltage appliances [5]. Around 2.5 billion people in developing countries rely on solid biomass such as fuel wood, charcoal, agricultural waste, and animal dung to meet their energy needs, primarily for cooking and lighting [6]. According to IEA [7], about three-quarters of the African population lacks clean cooking facilities. In Sub-Saharan Africa, more than 40% of the population lacks access to electricity, and in rural areas, more than 80% of the population is electricity-deprived [7]. The traditional use of biomass energy is inefficient and unclean and causes enormous negative socioeconomic and environmental consequences, like deforestation and land degradation [5]. Indoor combustion of solid biomass fuels has been shown to lead to high levels of exposure to fine particulate matter and gases like carbon monoxide. This is linked to an increased risk of respiratory and cardiovascular illness and may contribute to about 2 million early deaths globally per year [8,9]. By producing biogas, households could substitute the fuelwood used for cooking and significantly reduce mortalities from indoor smoke due to solid fuel use [9,10].

Biogas technology can contribute to three essential sectors in Sub-Sahara Africa: energy supply, sanitation, and crop productivity [11]. Biogas has immense potential to contribute to the energy supply, especially in rural

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areas [12,13], and serve to overcome energy poverty, a barrier to economic development in Africa [3].

Other benefits from biogas technology are reduced fossil fuel dependency, greenhouse gas emissions reduction, rural development, reduced use of chemical fertiliser, and reduced deforestation [12, 14,15]. The residue from the biogas digester is an excellent organic fertiliser that can replace chemical fertilisers and increase farm incomes [14,15]. Small-scale biogas production providing modern cooking fuels in rural communities has been successful in, e.g. China, India and Nepal. The support of government legislation to reduce forest degradation and introduce environmentally friendly energy to an ever-growing rural population was central to the successful implementation in these countries [16]. In many developed countries, biogas is converted into electrical and mechanical energy [17].

Significant investments in small-scale biogas technology in Sub-Saharan Africa have been made, but biogas technology is still not widespread [3,11]. In 2007, the 'Biogas for Better Life – An African Initiative' was launched to provide 2 million biogas installations by 2020. In 2013, a total of 29,500 digesters were installed [11]. There is limited evidence of these investments' socioeconomic or environmental benefits [15], manifested by hundreds of failed and abandoned biogas installations in the region [17,18],

Given the limited implementation of small-scale biogas technology in Sub-Saharan Africa presented above, the critical issue is understanding why significant scale-up has not occurred despite several programmes demonstrating the viability and effectiveness of biogas technology [3]. This study explores if the limited uptake of biogas technology in Africa is due to the predominant focus on providing heat and lighting and the lesser emphasis on electricity generation. The study's objective is to investigate the potential of small-scale biogas digesters to generate sufficient electricity to cover the daily electricity needs of rural households in Sub-Saharan Africa. To address the objective of the study, the following research questions were investigated:

• Can small-scale biogas digesters produce enough biogas to generate sufficient electricity to meet the daily energy needs of a rural household in Sub-Saharan Africa?

• What barriers must be removed to successfully implement small-scale biogas as a significant contribution to the electrification of rural Sub-Saharan Africa?

2. METHODS

2.1 Literature study

A literature study was conducted. Peer-reviewed articles were identified using the Scopus database searching for articles published since 2012 using search terms related to small-scale biogas systems and Sub-Saharan Africa. The literature study provides an overview of the potential benefits of small-scale biogas production in rural Sub-Saharan Africa. It presents the most common system designs and operations of small-scale digesters and energy requirements by rural households in that region. Finally, critical barriers to small-scale biogas technology are highlighted.

2.2 Case study

The potential of small-scale biogas production to generate sufficient electricity to cover the energy demand of a rural household in Sub-Saharan Africa was assessed based on equations and values of energy demand, potential biogas production and electricity generation obtained from current peer-reviewed scientific literature and information about local land use and potential substrate availability from a case study. The case study was conducted in Sekhutlane, an un-electrified village situated in the southern district of Botswana, about 250 km southwest of Gaborone (Fig. 1).

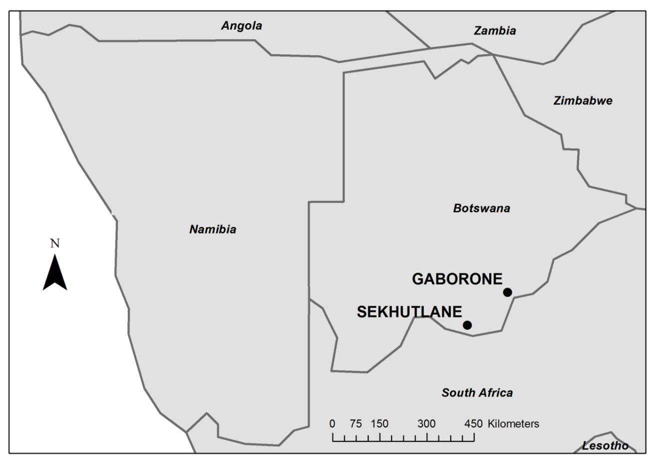

Fig. 1. The location of Sekhutlane village in southern Botswana [20].

Sekhutlane was established in 1985 and currently has a population of about 1,200 inhabitants in about 300 households [19]. The main occupation is cattle rearing and crop farming. Most households have between 10 and 20 heads of cattle, which are primarily free-roaming in the surrounding rangeland [20].

For this study, a hypothetical household-sized fixed dome biogas digester is fed daily with a substrate of cattle manure mixed with water (semi-continuous operation) (Fig. 2). The produced biogas is combusted in a 2 kW generator operated 24 hours per day, resulting in the generation of about 48 kWh of electricity. Parameters and their values used for the assessment are presented in Table 1. The available energy in the form of biogas and electricity generated by biogas combustion in a small-scale power plant was calculated. The equations used for the calculations are presented in Table 2.

3. RESULTS

The result presentation is divided into two sections. The first section presents a brief literature study of the design and operation of small-scale biogas digesters, electricity generation using biogas and energy demand in un-electrified rural households. The second section presents a case study assessing the feasibility of using cattle manure to generate sufficient electricity to cover a

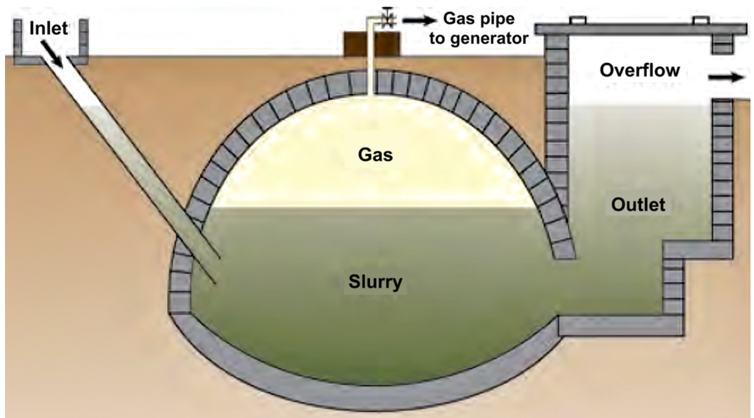

Fig. 2. Illustration of a small-scale fixed dome biogas digester after Vögeli et al. [21].

Table 1. Parameters and values used for calculation of the potential daily biogas production.

Parameter	Symbol	Value	Unit	Reference
Manure per cattle	CM	10-20	kg/day	[22]
Density of cattle manure	ρ	1000	kg/m^3	[23]
Number of cattle per household	Cnr	10-20	cattle	[20, 24]
Total solids substrate	TS	20	%	[22]
Volatile solids of TS	VS	80	%	[22]
Dilution feedstock: Water	DR	2	Parts	[21]
Organic loading rate	OLR	<2	kg VS/m^3 reactor volume and day	[21]
Hydraulic retention time	HRT	30	Days	[21]
Biogas yield	BPR	0.67	m^3/kg VS	[21]
Heating energy biogas	Hb	6	kWh/m^3	[21]
The overall efficiency of conversion of biogas to electricity	η	30	%	[21]
Biogas volume required to operate a 2 kW generator 24 h	Qbio	24	m3/day	[21]

Table 2. Equations used for calculations.

Parameter	Equation	Equation nr
Daily total biowaste available as feedstock (kg/day)	O = CM * Cnr	Equation 1
Water required per day (m^3/day)	W = (O/ ρ)*DR	Equation 2
Daily quantity of diluted feedstock (m^3/day)	Q = (O/ ρ) + W	Equation 3
VS of substrate per day (kg/day)	VSd = O * TS * VS	Equation 4
Substrate concentration in inflow, Kg VS/m^3	S = VSd * 1/Q	Equation 5
Liquid volume of digester	V = Q * HRT	Equation 6
Organic Loading Rate (kg VS/m^3 reactor volume/day)	OLR = Q * S / V	Equation 7
Biogas production per day (m^3 biogas/day)	Qbiogas = BPR * OLR * V	Equation 8
Biogas energy per day (kWh/day)	Ebiogas = Qbiogas * Hb	Equation 9
Available electricity per day (kWh/day)	Eelectricity = Ebiogas * η	Equation 10
Available power of electricity (kW/day)	Pelectricity = Eelectricity /24 h	Equation 11

rural household's energy needs, based on the off-grid rural village Sekhutlane in southern Botswana.

3.1 Literature study

The literature study presents the most common system designs and operations of small-scale biogas digesters, followed by energy requirements by rural households in Sub-Saharan Africa. Finally, some central limitations to small-scale biogas.

3.1.1 Design of small-scale biogas systems

There are three commonly used designs of biogas systems: fixed dome, floating drum, and plug flow reactors [17,26]. The fixed dome model developed in China, and the floating drum model developed in India have continued to perform until today [17]. The fixed dome digester design is the most deployed small-scale biogas technology in sub-Sahara Africa [4]. These reactors are small (5–10 m3) and are mainly used at the household level to deliver the energy demand for household cooking and lighting. The advantages of these reactors are that they are inexpensive compared to sophisticated systems, can be built with locally available material, are easy to handle and do not have moving parts prone to failure [3]. Generally, the initial investment costs decrease with an increase in digester size and a decrease in the total number of digesters installed [14]. Each digester type does not have facilities for mixing the slurry or maintaining a specific temperature in the digester. There are also no facilities to remove sand, stones and other non-digestible materials, which will accumulate over the years and decrease the volume of the digester, reducing its efficiency [3].

3.1.2 Operations small-scale biogas systems

A small-scale biogas digester is fed with organic materials, e.g. livestock manure, plant materials, food and agricultural waste, and energy crops [26]. Small-scale biogas digesters can be operated in three feed modes: batch, continuous or semicontinuous [17]. The operation of the bioreactor is characterised by three primary parameters: temperature, load and the duration of substrate retention in the biogas digester. The digester can be operated under psychrophilic (<20°C), mesophilic (20 – 35°C) or thermophilic (40 – 70°C) temperature ranges [4]. The load describes the content of dry organic matter (volatile solids, VS) loaded daily into the bioreactor per cubic meter of the working volume of the bioreactor [26]. Several studies present optimal organic loading rates (OLR) of manure in small-scale digesters. Abbas et al. [27] conducted a study in Pakistan using buffalo dung plus sheep waste with an OLR of 1.25 kg/VS per m3 and day. According to an extensive assessment of different small-scale biogas digesters, Baltrėnas and Baltrėnaitė [26] stated that the optimal OLR of cow manure is approximately 3.6 – 4.8 kgVS/m3/day. Rajendran et al. [17] noted that the OLR of cattle manure should be 2 – 3 kgVS/m3/day under mesophilic conditions, resulting in average biogas production of 0.26 – 0.55 m3/kgVS/day. The solid content in the digester can be either Wet Anaerobic Digestion (WAD), where the total solids (TS) of the substrate is less than 10% or Dry Anaerobic Digestion (DAD), where the TS of the substrate is greater than 10% [4]. According to Rajendran et al. [17], the solids concentration in household biogas digesters varies between 5% and 10%. The total volume of the bioreactor is usually 10% higher than the working volume to allow space for the gas to accumulate [26]. The hydraulic retention time (HRT) is the time the substrate is kept in the digester, and it varies between 20 and 100 days for mesophilic household digesters [17]. Several studies recommend an HRT of 30 days for small-scale digesters [17,21,26]. The size of the bioreactor depends on the OLR, HRT and the total volume flow of the substrate. The TS of cattle manure is about 20% of the wet mass, and the VS is about 80% of TS [22]. For a solid substrate concentration of 5 – 10%, the substrate must be mixed with water in 1:1 to 1:4 parts, depending on the TS of the feedstock [21].

3.1.3 Energy requirements

To determine the potential of small-scale biogas production, the energy requirements of rural households intended to adopt the technology must be understood. Households need different forms of energy for various services; thus, a combination of sources providing heat and electricity is required to meet the demand [5]. Results presented by Msibi and Kornelius [10] show that a low-income South African household cooking with fuelwood requires 27 MJ/day and has a total energy demand of 68 MJ/day. This is equivalent to 2,500 L/day per household of biogas for cooking and 6,250 L/day/household for completely substituting conventional domestic fuels [10]. A study of a medium-sized farm in Jordan by Rajendran et al. [17] estimated the monthly energy consumption for various purposes to be about 1,282 kWh.

3.2 Case study

The case study is based on information about livestock herding by communal subsistence farmers in Sekhutlane village in rural Botswana [20] and rural Namibia [24]. Three scenarios were defined: Scenario 1: 10 head of cattle and 10 kg manure per head of cattle per day; Scenario 2: 20 heads of cattle and 10 kg of manure per head of cattle and day; and Scenario 3: 40 heads of cattle and 10 kg of manure per head of cattle and day. The results of the calculations are presented in Table 3.

Table 3. Results of potential biogas production calculations and daily usable electricity for the three scenarios.

Parameters	**Scenario 1: 10 heads of cattle, 10 kg manure/head and day**	**Scenario 2: 20 heads of cattle, 10 kg manure/head and day**	**Scenario 3: 40 heads of cattle, 10 kg manure/head and day**
Digester volume (m^3)	10	20	40
Daily quantity of diluted feedstock (m^3)	0.3	0.6	1.2
Water requirement per day (m^3)	0.2	0.4	0.8
Biogas production per day (m^3/day)	11	21	43
Usable electricity per day kWh/day	19	39	77
Available power of electricity kW	0.8	1.6	3.2
Possible to operate a 2 kW generator 24 hours a day (>48 kWh/day)	No	No	Yes

Table 4. Comparison of energy requirements from the literature and calculated daily usable electricity from a 2 kW biogas-genset system based on a herd of 25 cattle and 10 kg of collected manure.

Case	**Energy use**	**Energy requirement**	**Electricity requirement (kWh/day)**	**Biogas-genset meets energy requirement**
Rural South Africa [10]	Cooking	27 MJ/day	7.5	Yes
Rural South Africa [10]	All household energy	68 MJ/day	18.9	Yes
Medium-sized farm in Jordan [17]	All energy for farm	1282 kWh/month	42.1	Yes

Table 5. The Power rating, time of operation and electricity use per day of common household appliances [28].

Appliance	**Power rating (W)**	**Time of operation (h)**	**Total electricity kWh/day**
Ceiling fan	50	12	0.6
Refrigerator	500	24	12
Electric stove	1000	4	4
Electric kettle	1200	0.5	0.6
5 Light bulbs, LED	45	12	0.5
TV	100	4	0.4
5 Phone chargers	100	8	0.8
Total	**2795**		**18.8**

Based on the analysis, the break-even value for 24 h electricity supply using a biogas-powered 2 kW generator is 25 heads of cattle, producing at least 10 kg of collected manure per head per day. This number of cattle and genset would provide 48 kWh of electricity per day. A comparison of a system generating usable electricity of 48 kWh/day with the energy requirements given by Msibi and Kornelius [10] and Rajendran et al. [17] is presented in Table 4. The power rating, time of operation and electricity use per day of common household appliances are shown in Table 5.

4. DISCUSSION

This study investigates the potential of small-scale biogas digesters to generate sufficient electricity to cover the daily electricity needs of rural households in Sub-Saharan Africa. Two questions guided the analysis: Can small-scale biogas digesters produce enough biogas to generate sufficient electricity to meet the daily energy needs of a rural household in Sub-Saharan Africa? and What barriers must be removed to successfully implement small-scale biogas as a significant contribution to the electrification of rural Sub-Saharan Africa? This study confirms the findings of Tucho and Nonhebel [5] and Rupf et al. [11] that biogas technology has the potential to be a viable contribution to the energy mix in rural Sub-Saharan Africa, especially in un-electrified areas or where competing sources of energy are limited or have a high cost [12]. However, the literature study shows that the uptake of biogas technology has been limited in Sub-Saharan Africa. Several studies present common barriers to slow uptake: inadequate substrate supply, lack of water and variable temperatures, high initial costs, poor technical quality, intense labour operations and maintenance, and no policy support [3,5,17,18].

The case study presented here shows that the minimum requirement to power a 2 kW generator 24 h/day is 25 cattle producing at least 10 kg manure per head of cattle and 500 L of water to dilute the daily feedstock.

The comparison of generated electricity and energy requirements presented in Table 4 shows that it is possible to meet the daily energy requirements of low-income households in South Africa, as described by Msibi and Kornelius [10]. The generated electricity from the waste of 25 cattle would not be sufficient to provide all the required energy by the medium-sized farm in Jordan investigated by Rajendran et al. [17].

Based on the values presented in Tables 4 and 5, a household with 10 heads of cattle using a generator with a power of 0.8 kW would be able to produce 19 kWh of electricity per day, which would be sufficient to power a refrigerator 24 h/day and allow usage of a few other appliances presented in Table 5 if the total Wattage required at any time is below 0.8 kW. This system would not be able to power all appliances in Table 5 for 24 h/day but would still significantly improve the household's energy situation.

So, what barriers must be removed to improve the uptake of biogas technology in Sub-Saharan Africa? Parawira [3] concludes that large-scale adoption of biogas technology requires establishing national institutional frameworks that can provide financial and technical support and training and develop required policies. Foreign donor organisations often introduce biogas technology in collaboration with the central government in a developing country. Funding is provided in the form of short-term project funding. Most projects have good intentions but are often conceived without adequately understanding the targeted users' needs, problems, capabilities and priorities [3]. Therefore, these projects must be developed in collaboration with the intended users of the technology and local support organisations. The collaboration between stakeholders throughout the project is a crucial determinant of success or failure. The involvement of the household members, the owners of the biogas system, is the most critical factor, as the owners' understanding and engagement are directly correlated to the outcomes [18].

The limited local spare parts supply is another factor contributing to failed biogas projects. Parawira [3] presents findings from an assessment of a biogas demonstration project in Zimbabwe where spare parts had to be imported from abroad and paid with foreign currency to maintain the demonstration installation. To ensure the long-term local availability of spare parts and supplies required for operations and maintenance, local supply of spares must be part of the project deliverables.

Tucho and Nonhebel [5] and Parawira [3] addressed the households' limited access to feedstock. Many households in Sub-Saharan Africa do not have enough feedstock to operate their digesters. This is in line with the observations made in Sekhutlane, where most households have herd sizes of 10 – 20 heads of cattle. To increase the amount of manure available, animals should be penned for more effective dung collection [3]. Tucho and Nonhebel [5] suggest a centralised biogas digester at the village level, especially in areas where houses are clustered; a community plant might be more feasible. With a centralised system, feedstock can be combined into one production system, increasing production reliability and efficiency [3]. Centralised systems benefit from a lower unit of investment cost, lower labour requirements for operations and the availability of different biowastes for sharing [5].

5. CONCLUSIONS

This study investigated if small-scale biogas digesters can produce enough biogas to generate sufficient electricity to meet the daily energy needs of a rural household in Sub-Saharan Africa. Barriers that must be removed to successfully implement small-scale biogas in the region were identified. The study is unique because it examines the potential of small-scale biogas digesters to produce enough electricity for rural households in Sub-Saharan Africa. While most previous studies have focused on using biogas for cooking and heating, this study addresses the issue of electrification in rural areas.

The findings suggest that at least 25 cattle are required to generate sufficient biogas to power a 2 kW generator 24h/day. However, this poses a challenge as most rural households in Sub-Saharan Africa have smaller herds of cattle. Nevertheless, the results show that a herd of 10 cattle provides enough biogas to power all electrical household appliances presented in Table 5. This would significantly improve the household's energy situation.

To Improve the uptake of small-scale biogas technology in Sub-Saharan Africa requires:

- Establishing national institutional frameworks that can provide financial and technical support, training, and develop required policies.
- Projects must be developed in collaboration with the intended users of the technology and local support organisations. The collaboration between stakeholders throughout the project is a crucial determinant of success or failure.
- The involvement of the household members, the owners of the biogas system, is the most critical factor, as the owner's understanding and engagement are directly correlated to the outcomes.
- To ensure long-term local availability of spare parts and supplies required for operations and maintenance of these systems must be part of the project deliverables.
- Animals should be penned for a more effective collection of dung.
- Centralised biogas systems on the village level combine feedstock into one production system, producing reliable, efficient, and sufficient volumes of biogas.

Building on the findings presented here, the next step would be to conduct an in-depth assessment of successful installations of small-scale biogas systems to determine what factors led to the success. A second step would be to conduct a field-based cost-benefit analysis of a pilot installation of a small-scale biogas digester connected to a small genset in rural Sub-Saharan Africa, taking the actions required to improve the uptake of biogas technology into consideration.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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