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Life Cycle Assessment and Return on Investment of Biogas Utilization in Dairy Farming Areas of Tanzania

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Abstract

A case study was conducted on a locally installed biogas system as a renewable energy source, aimed at examining off-grid power sources suitable for rural Tanzania. The study estimated energy consumption and CO_2 emissions associated with the procurement of materials, plant construction, and plant operation for a domed biogas plant, widely used in rural areas of Tanzania. The results indicate that the evaluated dome biogas plant exhibits a good energy balance, with an estimated energy payback time of 3 - 4 years, owing to the absence of energy inputs. Moreover, grazing was found to significantly reduce CO_2 emissions compared to leaving cattle manure unattended. However, the cost-benefit ratio of using biogas as an alternative to LPG was only 1.2, primarily due to the burden of equipment costs. Future considerations should include exploring advanced applications such as power generation, transport fuels, and thermal use, which could potentially offer a clean and modern energy source to replace LPG.

Keywords

Renewable Energy, Biogas, Cow Slurry, Life Cycle Assessment, Investment, Tanzania

1. Introduction

To address the urgent issue of global warming, it is necessary to minimize the use of fossil fuels. At the same time, however, it is essential to secure energy sources economically, presenting modern society with the major problem of balancing economic and environmental concerns. The use of renewable energy is recommended as a potential solution. Although dramatic technological advances are making renewable energy economically viable, it still does not account for a high proportion of global energy consumption. In particular, the introduction of renewable energy in the heat sector, which accounts for half of energy demand, has not noticeably progressed (REN21, 2022).

Biomass constitutes a significant portion of renewable energy utilized for heat generation. Among non-fossil fuels, traditional biomass usage represents 11.9%, while sustainable bioenergy, categorized as modern renewable energy, comprises 6.9% (IRENA IEA REN21, 2020). Although the conventional use of firewood falls under traditional biomass (Goldemberg & Teixeira Coelho, 2004), the adoption of biogas derived from agricultural residues and solid waste, classified as sustainable bioenergy, is gaining traction, albeit on a modest scale. Biogas technology involves converting organic waste into combustible gas and organic fertilizers through anaerobic processes. Its application extends to cogeneration for electricity and heat provision, as well as emerging usage in transport fuels and domestic cooking. The environmental implications of biogas production and usage are extensively reviewed by Hijazi et al. (2016). Life Cycle Assessments (LCAs) conducted on 15 European cases revealed that methane gas production yields lower Greenhouse Gas (GHG) emissions compared to conventional composting methods. Notably, biogas systems utilizing livestock manure are highlighted for their effectiveness in circumventing environmental impacts during production (Stucki et al., 2011; Hamelin et al., 2010).

African countries, amidst ongoing economic and population growth, are garnering global attention as potential major markets. However, development in rural areas tends to lag behind rapidly modernizing urban areas, widening economic disparities. Sub-Saharan African countries, including Tanzania, are considered regions where poverty is most acute. Specifically, Tanzania grapples with a notable deficit in power supply capacity, evident in the rural electrification rate stagnating at 24.5% (The United Republic of Tanzania, 2019/20). Additionally, biomass burning remains the primary energy source for approximately 90% of Tanzania's population (The World Bank, 2019; 2021). In rural areas with low electrification rates, biogas production from livestock manure emerges as an exceptionally effective energy procurement method. Anaerobic biogas production thrives in warm climates and is viable even in arid and semi-arid regions with erratic water supplies (Tanzania Domestic Biogas Programme, 2013), making its implementation in Tanzania a possibility. Various initiatives have aimed to promote biogas utilization in Tanzania, particularly in the Northern Zone during the 1990s and 2000s. According to Hewitt et al. (2022), small-scale biogas units hold the potential to enhance access to clean, modern energy sources for cooking, heating, and lighting. However, efforts to promote biogas have yielded limited success. Numerous biogas plants have been abandoned due to factors such as poor construction and installation, suboptimal feeding practices, inadequate maintenance, and insufficient training provision and knowledge (Hewitt et al., 2022). However, as energy conversion from cattle manure can help promote electrification in rural Uganda, David et al. (2022) has recently reported simulation results on the optimisation of a system that produce high profits.

We have examined cases of locally installed renewable energy sources to assess suitable off-grid power sources for rural Tanzania. Thus far, we have investigated photovoltaic installations and identified issues such as low generation efficiency resulting from system over-specification and underutilization of equipment due to immature operation and maintenance systems (Tsuchiya et al., 2020). This study evaluates the feasibility of biogas systems, which are gaining popularity in dairy farming areas of Northern Tanzania, focusing on environmental impact and investment payback. Biogas feasibility in rural areas will demonstrate its potential as a renewable energy source enabling energy procurement through economically advantageous means while reducing CO_2 emissions.

2. Survey Site and Evaluation Method

2.1. Survey Site

Arusha, the commercial hub of Northern Tanzania, boasting the largest agricultural population, was selected as the study site. Northern Tanzania accommodates diverse nomadic communities, including the Maasai, for whom access to energy sources poses a significant challenge. The Centre for Agricultural Mechanisation and Rural Technology (CAMARTECH), a national organization championing agricultural technology, is headquartered in Arusha and actively promotes biogas initiatives. CAMARTECH's efforts have resulted in a proliferation of biogas plants in the region, supported by various national institutions and non-governmental organizations (NGOs).

CAMARTECH has adopted a dome-type biogas system due to its extensive installation history, ease of construction and operation, and straightforward technology transfer. Depending on the supply capacity of cattle manure, the digester volume accommodates three plant sizes: 6 m^3, 9 m^3, and 13 m^3 (**Table 1**). Domes (6 m^3), which are most suitable for typical farmers with three to four dairy cows, are the most widespread. Therefore, the evaluation in this study was carried out on a 6 m^3 dome biogas plant in operation in Arusha.

Table 1. Size and processing capacity of CARMATECH's biogas plants.

Digester size m^3	Daily gas production (DS-SS) Liters/day	Daily dung feeding (min-max) kg/day	Water/Urine ratio Liters/day	
			Initial	Normal
6	2625 - 3410	60 (50 - 75)	60	15 - 20
9	3920 - 5095	90 (75 - 112)	90	21 - 30
13	5670 - 7370	105 (108 - 162)	105	31 - 35

2.2. Evaluation Method

Life cycle assessment (LCA) is an effective method for quantifying the materials and energy consumed throughout the life cycle of any product or service, as well as assessing their environmental impact. In product LCAs, the cumulative primary energy demand is calculated over the life cycle. Energy payback time (EPBT) refers to the duration required for a renewable energy system to generate the same amount of energy used in its production process (Frischknecht et al., 2015), and it is expressed as follows:

$$\text{EPBT} = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})/\{(E_{agen}/h_G) - E_{aoper}\} \quad (1)$$

where E_{mat} represents the primary energy demand for producing the components of the biogas system; E_{manuf} represents the primary energy demand employed during the system manufacturing process; E_{trans} represents the primary energy demand for transporting the materials used during the product life cycle; E_{inst} represents the primary energy demand used for the installation of the system; E_{EOL} represents the primary energy demand for end-of-life management; E_{agen} represents the annual electricity generation; h_G represents the grid efficiency (i.e., the average primary energy to electricity conversion efficiency at the demand site); E_{aoper} represents the annual energy demand for operation and maintenance in primary energy terms. In this study, the evaluation with EPBTs was applied, although the study is not about the generation of electricity from biogas but the use of heat. The energy consumption and cost-benefit associated with biogas production were estimated for a domed biogas plant, widely used in rural Tanzania. The assessment scope encompassed the plant construction stage, involving the procurement of materials required for the biogas plant's construction, plant construction excluding manpower and gas pipeline to the demand area, and the plant operation stage for daily gas production (**Figure 1**). The materials and energy required for each stage were estimated. Based on interviews with plant builders, the distance between the plant construction site and the material procurement point was set at 20 km, and truck transport was considered. As the one-way trip would be made with empty loads, it was assumed that the distance of one transport would be 40 km and that four round trips would be made for all material procurement. The operation of the plant, that is, the production of biogas, requires water as well as waste cattle manure, but no energy input is required as cattle urine and water from the reservoir are used and these are brought in by hand. Data provided by CAMARTECH and actual data from beneficiaries were referred to for the volume of materials used in plant construction and the material balance associated with gas production. Emission factors are shown in **Table 2**, and these values refer to the manual provided by the Japanese Ministry of the Environment (Ministry of the Environment Japan, 2023). Energy consumption (primary energy equivalent) and CO_2 emissions (100-year index, IPCC 2007) were estimated using the LCA calculation software MiLCA ver2 (Sustainable Management Promotion Organization, Tokyo).

In conducting the cost-benefit analysis, a discount rate of 10% was utilized. Monetary costs included capital costs for constructing the 6 m^3 biogas plant, estimated at TZS 2.4 million. Construction is projected to take a maximum of six

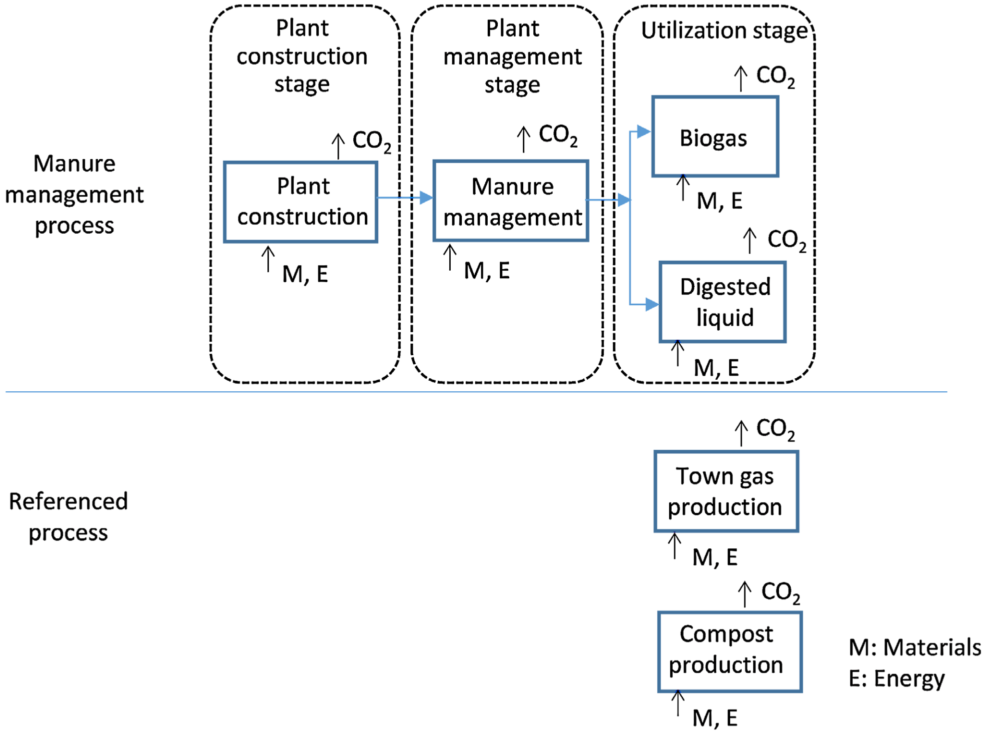

Figure 1. Flow and boundary condition of the manure management process and referenced production flow.

Table 2. List of coefficients for greenhouse gas emissions associated with livestock waste management.

Category/Activity	Unit	Emission coefficients
CH_4 from manure excreted by grazing cattle	tCH_4/Cattle	0.0013
CH_4 per unit of organic matter*[a] form the deposition of manure by dairy cow	tCH_4/t	0.038
CH_4 from compost production	tCH_4/t	0.00096
CH_4 from town gas production	tCH_4/PJ	0.26
N_2O from manure excreted by grazing cattle	tN_2O/Cattle	0.00018
N_2O per unit nitrogen*[b] from the deposition of manure by dairy cow	tN_2O/t	0.038
N_2O from compost production	tN_2O/t	0.00027

[a]Reference value for organic matter content in dairy cattle manure is 16.5%. [b]Reference value for the annual nitrogen emissions in dairy cattle manure is 0.072 tonN/cattle/year.

months. Other O&M costs were factored in, such as labor for fetching and feeding the biogas plant and maintenance costs of TZS 50,000 every three years. Benefits were derived from savings on purchasing an LPG cylinder, which has an economic lifespan of 10 years. It is assumed that a 15 kg LPG cylinder is adequate for one month's use. Cylinder maintenance costs are estimated at TZS 20,000 every two years.

Based on the gathered data, an Excel cost-benefit analysis model was developed, where costs and benefits were discounted at a rate of 10% over a 20-year estimation period. A Net Present Value was then calculated.

3. Results and Discussion

3.1. Energy Consumption and Energy Payback Time for Biogas Plant Manufacturing

Based on actual data from CAMARTECH and beneficiaries, the inventory data used for the LCA calculation are summarised in Table 3. The energy consumption associated with the production of the domed biogas plant with an internal volume of 6 m^3 and the gas pipeline facility to the consumption point was calculated to be 1.04×10^5 MJ/unit.

Biogas plants are built manually, so there is no energy inputs associated with their construction. Therefore, the total energy consumption for methane gas production is low, and accordingly CO_2 emissions are also low. The use of environmentally hazardous fossil fuels is limited to fuels associated with the transport of materials. For transport, the fuel consumption for the return trip was taken into account, as another use could not be identified for the return trip.

Table 3. Unit process data of biogas plant (6 m^3) production.

Classification	Item	Unit	Quantity
Resources	Sand for aggregate	ton	6
	Gravel	ton	4
	Stone	ton	3
	Cement	ton	0.9
	Bric	ton	3.2
	Lime	kg	125
	Chemical products (waterproofing agents)	kg	5
Transportation	Metal products	kg	20
	7 ton-truck	km	120

According to CAMARTECH's technical document (Tanzania Domestic Biogas Programme, 2013), a 6 m^3 domed biogas plant is stated to produce 2625 - 3410 L/day of methane gas from 60 kg/day of cattle manure. In interviews with beneficiaries, many respondents stated that they keep four dairy cows and can supply 40 kg of cattle manure per day. The recovery rate of cattle manure was considered to be limited due to the lack of controlled rearing. Assuming a typical case of 40 kg/day of cattle manure supply and a methane gas production rate of 1750 - 2273 L/day, the methane gas combustion energy of 55.8 MJ/kg would yield 25,550 - 33,215 MJ/year of methane gas. An energy payback time of 3 - 4 years is required, and considering that a domed biogas plant can be used for more than 20 years without significant maintenance, a sufficiently positive energy balance is expected.

3.2. Environmental Impact Assessment

Livestock manure is commonly used as compost, even when not employed for biogas production, due to its nitrogen and organic matter content. Moreover, biogas production yields effective fertilizer in the form of digested liquid alongside methane gas. The emission of greenhouse gases in these processes is discussed. According to a handbook published by the Japanese Government (Ministry of the Environment Ministry of Economy Trade and Industry Japan, 2023), CH_4 and N_2O emissions from manure excreted by grazing cattle are reported to be 0.0013 ton CH_4/head/year and 0.00018 ton N_2O/head/year. In contrast, when manure is treated by sedimentation, the amount of methane and nitrous oxide derived from manure is estimated to be 0.038 ton CH_4/ton-organic matter and 0.038 tonN_2O/ton-N, respectively. In Japan, sedimentation processes involve dedicated compost sheds and shovel loaders for turnover, whereas in Tanzania, cattle manure is piled in the open and occasionally stirred by hand. Therefore, no material or energy input was assumed to be involved in the deposition process. In the biogas production addressed in this study, manually collected cattle manure is fed into a domed digester buried underground, preventing methane or nitrous oxide release into the atmosphere. This approach also avoids the release of acidic gases such as ammonia into the atmosphere, a factor beyond the scope of this study. The lifetime of the biogas plant was set at 20 years. Greenhouse gas emissions were compared across three scenarios: grazing (Case 1), sedimentation treatment (Case 2), and biogas production (Case 3). Note that for Case 1, CH_4 and N_2O emissions from manure excreted by cattle were calculated and converted to CO_2 emissions (global warming potential of 28 for CH_4 and 265 for N_2O), assuming grazing of four cows. For Cases 2 and 3, greenhouse gas emissions were estimated for 40 kg/day of manure that can be collected per day. This amount of manure corresponds to a quarter of the manure discharged per day, according to the Japanese Ministry of the Environment manual. In other words, the remaining three-quarters is left unattended, thus imposing an environmental burden similar to that of grazing; this portion was accounted for as No-management in the CO_2 emissions estimates.

The results are depicted in **Figure 2**, where methane and nitrous oxide emissions are converted into CO_2 emissions (with a global warming potential of 28 for CH_4 and 265 for N_2O). Greenhouse gas emissions during the treatment process are low with grazing and increase significantly with sedimentation treatment. However, CO_2 emissions associated with sedimentation treatment are almost halved, as emissions from sedimentation treatment are offset by compost production. Furthermore, GHG emissions could be reduced by implementing measures to control gas emissions, such as constructing compost sheds.

In Case 3, the CO_2 emissions associated with the construction of the biogas plant were estimated at 9990 kg-CO_2, with an estimated annual CO_2 emission of

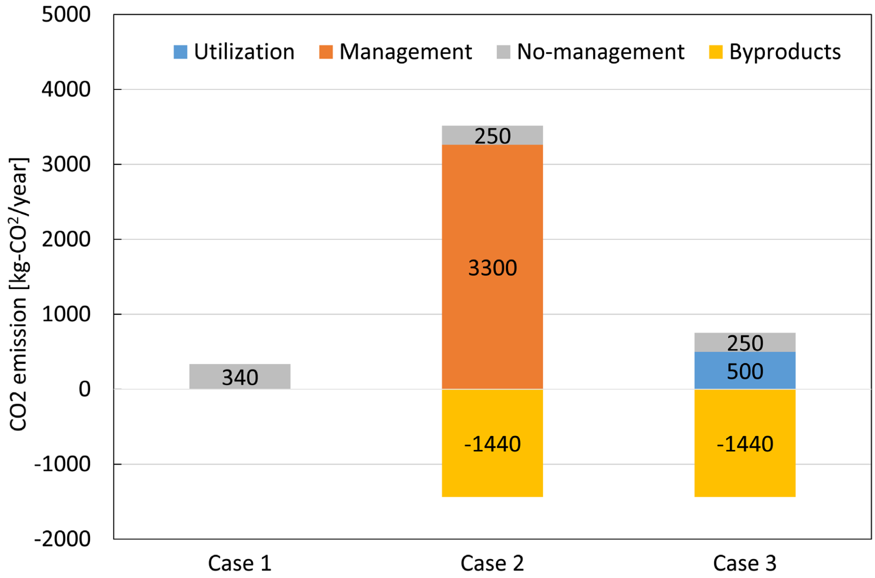

Figure 2. Comparison of CO_2 emissions from different cattle manure treatments.

500 kg-CO_2, assuming a plant lifetime of 20 years. Similar to Case 2, considering compost production results in a negative environmental impact. This indicates that methane gas production is highly effective in reducing GHG emissions. For a more accurate assessment, it is necessary to estimate emissions at the utilization stage, depending on the quantity and type of compost obtained. The impact of transport for spreading compost and liquid manure during the utilization stage has also been noted (Hishinuma et al., 2008). However, as compost and liquid manure applications in rural areas of Tanzania are often carried out manually, this estimate does not account for emissions associated with transport for spreading.

3.3. Cost-Benefit Analysis

A cost-benefit analysis was conducted to compare the use of LPG and biogas (6 m^3 plant) with the LPG gas usage for a 15 kg cylinder, sufficient for a 5-member household for one month. This choice was made to accommodate the failures in biogas systems and the recent introduction of LPG as an alternative energy source. The benefits are assessed based on LPG usage. The current purchase cost of an empty 15 kg LPG cylinder is TZS 45,000, with the gas itself costing TZS 58,000.

The cost-benefit analysis focuses on the construction cost of the biogas plant in comparison to LPG usage. Other benefits, such as environmentally friendly gas, minimal operational risks associated with biogas, and the cost of cookers, are disregarded. The costs of cookers for LPG use are expected to exceed those for biogas and its utensils.

Based on the 20-year analysis of the reactor's lifetime, it was established that the payback period is 11 years (Figure 3), and the cost-benefit ratio is 1.17 (Table 4).

As shown in Figure 3, cumulative return, which is the sum of benefits and costs, becomes positive in year 10, indicating the payback period of the

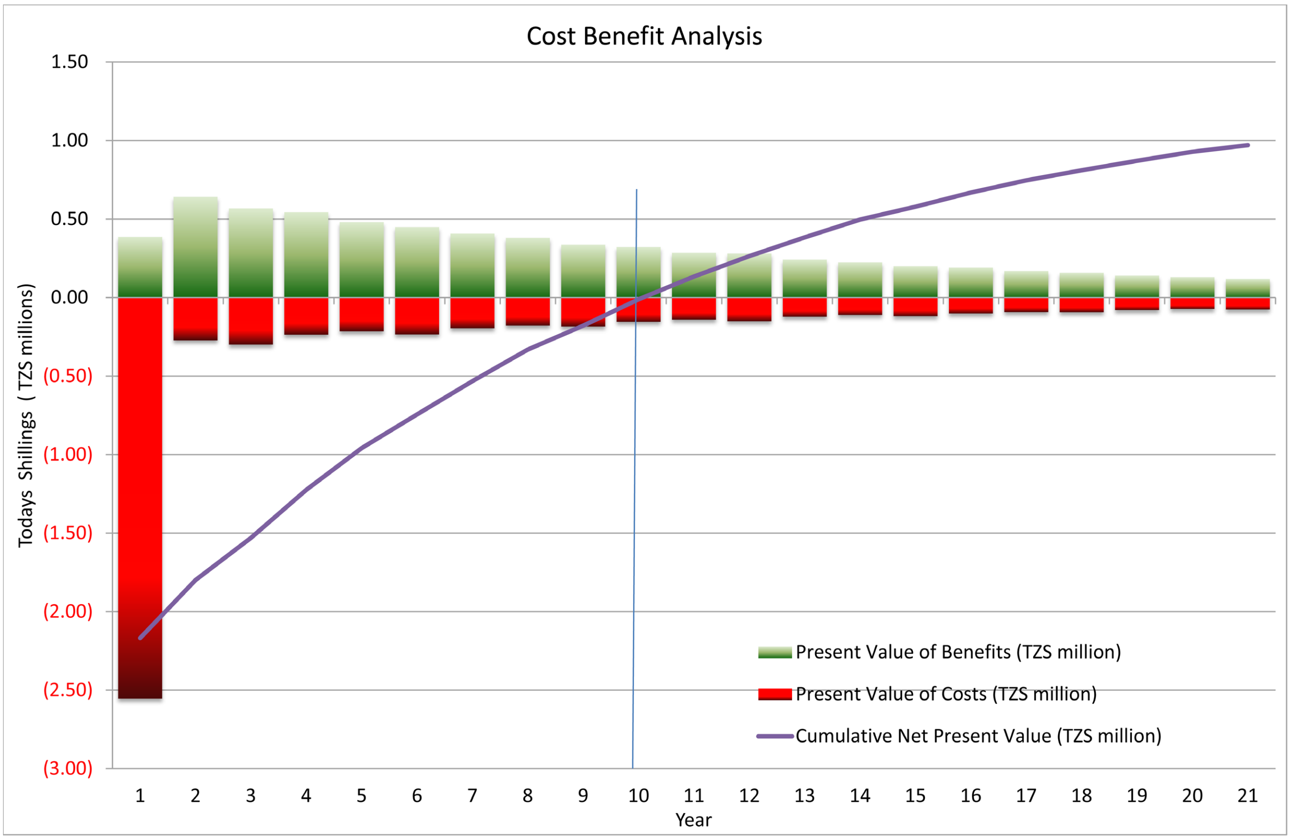

Figure 3. Cost benefit analysis of 6 m³ biogas plant.

Table 4. Summary of the cost benefit analysis for a 6 m³ biogas plant.

Key Assumptions:		
Discount Rate	10.00%	
Appraisal period (years)	20	years
Summary of the Results of the Analysis:		
Capital Costs	2,400,000	TZS
Whole of Life Costs	10,780,793	TZS
Present Value of Benefits	6,649,372	TZS
Present Value of Costs	5,678,725	TZS
Benefit Cost Ratio	1.17	
Net Present Value	970,647	
Payback	11	Years

investment, or the time it takes for positive cash flow to exceed the costs of project. The study evaluates the feasibility of implementing biogas systems in rural Tanzania, focusing on a 6 m³ dome biogas plant in Arusha. However, the study's scope is limited to this specific plant size and may not fully represent the diversity of biogas installations based on various sizes or challenges across different regions of Tanzania. Additionally, reliance on data provided by CAMARTECH and beneficiaries introduces potential biases and assumptions regarding cattle manure supply and methane gas production rates, which may change based on weather conditions, feedstock, and the size of the cow, among other factors.

The environmental impact assessment primarily focuses on greenhouse gas emissions without thoroughly examining other ecological factors like water usage, soil quality, and biodiversity. External factors such as government policies, market dynamics, and technological innovations are not adequately considered, potentially limiting the study's general applicability and relevance across countries or regions.

Future studies may address these limitations to enhance the robustness and applicability of their findings and recommendations. Future research may include a more diverse sample of biogas installations and comprehensive data validation, which would provide a more accurate understanding of biogas system challenges and benefits across Tanzania. Additionally, socio-economic considerations and evaluating the long-term viability of biogas plants may benefit policymakers, researchers, and practitioners involved in promoting renewable energy adoption in Tanzania.

4. Conclusion

A case study of a domed biogas system installed in Arusha, Northern Tanzania, as a self-sustaining heat source was conducted. The results showed that the biogas plant under evaluation had a good energy balance, as there were no energy inputs other than equipment manufacturing, and the energy payback period was estimated at 3 - 4 years. It was also demonstrated that CO_2 emissions are significantly reduced compared to leaving cattle manure unattended. However, the cost-benefit ratio of biogas as a substitute for LPG was only 1.2 due to the burden of equipment costs.

For more efficient biogas production, it is recommended that cattle be managed in barns rather than grazed. In Tanzania, only 25% of the manure that is originally excreted is recovered. Management in barns would simultaneously improve cattle manure recovery rates and significantly reduce the workload. However, keeping cattle in barns creates a new economic burden in terms of feed supply and management costs. In LCA assessments for methane gas production, the starting point of the assessment is the waste product—cow manure—and the material and energy inputs associated with rearing do not need to be considered. This is because dairy cows are reared to obtain milk, not cow manure. However, the economic burden is real, and therefore the balance between workload and economics needs to be considered.

Although the use of methane gas in Arusha is exclusively for cooking, it can be converted into electricity, a highly versatile form of energy, by introducing gas generators. By converting gas into electricity and storing it in batteries, energy can be stored at a higher density than with gas alone. The conversion of gas into electricity, which can be used as needed, can be an extremely effective energy resource for nomadic people who have limited access to energy resources.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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