Article

Biomethane-powered Energy-as-a-Service innovation for improved access to off-grid cooling for dairy processing in Uganda (BioCool project)

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Abstract

As dairy farms expand in Uganda, farmers and processors struggle to safely store and process milk and dairy products due to a grossly limited cold chain. The BioCool project piloted a biomethane-powered off-grid cooling innovation, leveraging the local application of digesters in Uganda. A stepwise approach to optimising the energy output from traditional dome-type digesters in Uganda was implemented, including (i) installing a mechanical stirrer and external gas storage bag to improve the digestibility of and biomethane recovered from cow dung (ii) modifying a refrigerator originally designed to run on liquefied petroleum gas (LPG) to directly run on biomethane to enable off-grid cooling and (iii) developing an Energy-as-a-Service (EaaS) tool to provide efficient energy costing. Installing the stirrer and storage bag increased biomethane yield by 28.3% and enabled 35% volatile solids destruction compared to 4% without modifications. Cooling down to -6°C was achieved, and only 7.7% of biomethane produced would be required to deliver the 4°C temperature required for milk cooling. The EaaS tool demonstrated opportunities to scale biomethane energy solutions across the entire agricultural sector. Therefore, BioCool innovation can be the game-changer technology for sustainable off-grid cooling to boost productivity in the dairy industry and the agricultural sector at large.

Keywords: Biomethane; Clean Cooling; Anaerobic Digestion; Milk; Dairy; Off-grid Cooling.

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1. Introduction

Uganda's dairy sector, currently valued at $3.8 billion with 3% annual growth rate, plays a vital role in the country's agricultural landscape [1]. Livestock in general contributes about 16.9% of Uganda’s agricultural gross domestic product (GDP), and the dairy sector accounts for 72% of livestock GDP and 84% of livestock export value, estimated at $264 million in 2023 [1]. The dairy sector has experienced significant growth in the number of cattle heads over the past decade. National herd size grew by 29%, from 13.02 million heads of cattle in 2013 to 16.7 million heads of cattle in 2023, resulting in 103% increase in milk production: from 1.9 to 3.85 billion litres respectively. As of 2024, milk production reached 5.4 billion litres, showing an impressive 40% growth against the 2023 production record and is the second largest contributor to Uganda’s agricultural export value. Therefore, milk and dairy products play a crucial role in combating food insecurity in the region.

A critical resource for dairy processing is access to electricity. However, only 32.9% of the Ugandan population has access to electricity [2]. Uganda’s milk market chain typically involves the collection of milk from farmers to the collection centres at certain collection times by small-scale traders, which is then transported to milk processing plants by large-scale traders [3]. Poor electricity access limits the use of efficient cooling facilities to enable processing and storage across the entire milk market chain, resulting in post-harvest losses, reduced food availability and economic losses.

At the farm level, farmers cannot efficiently preserve the freshness of their milk and extend its shelf life until the collection days, which exacerbates spoilage, leading to significant economic losses. Consequently, milk produced outside collection windows is typically processed by boiling and sold raw through informal markets. The informal market caters to approximately 70% of milk produced in Uganda, without adhering to international quality standards and critical practices like pasteurisation, leading to significant spoilage and post-harvest losses. Milk moved through the informal market is often regarded as lower quality, reducing the market value and associated price. At the end of each day, farmers are forced to discard unsold or unused dairy products, resulting in additional post-harvest and financial losses [4].

Only 30% of the milk produced moves through the formal milk market chain through milk collection centres (MCCs) and processing centres. However, about 50% of the MCCs are off-grid and, therefore, are operated entirely on diesel generators. Due to erratic power supply, the MCCs connected to the electricity grid still rely on back-up diesel generators for up to eight hours daily, which makes up 40% of their operating costs [5]. The high cost of diesel reduces the operating capacity of dairy processing centres in Uganda. Uganda has 145 dairy processing facilities with a total installed capacity to process 3.4 million litres of milk daily, but currently operates at 2.3 million litres daily, 68.7% efficiency [1].

With the progressive growth in the dairy sector and the sector's potential to significantly contribute to food security and socio-economic growth in the region, it is now crucial to develop affordable off-grid cooling solutions to help maintain the quality and safety of milk (and other dairy products) throughout the market chain. By addressing the cooling-access challenge, Uganda can advance its dairy industry, reduce losses, increase processing capacity, improve economic outcomes, and ensure the availability of safe and high-quality milk for consumers.

Anaerobic digestion (AD) technology can provide sustainable off-grid clean cooling access to advance the dairy sector. AD is a natural process during which microorganisms break down organic materials (materials of plant or animal origin) to produce a gas mixture known as biogas and a liquid by-product, called digestate or digested slurry. Biogas comprises 50 – 70% methane (CH_4) and 30 – 50 % carbon dioxide (CO_2). The CH_4 in the biogas can be burnt to recover energy, making biogas a renewable, low-carbon energy source. The digestate retains the nutrients present in the parent organic material, which serves as an organic fertiliser to support plant growth. Notably, various organic materials can be utilised for AD, such as animal manure and market wastes, making it a technology with multi-fold advantages, providing affordable and low-carbon fuel, organic fertiliser and waste management. Uganda is one of the few countries in Sub-Saharan Africa (SSA) exploiting the AD technology to provide household cooking and lighting, with over 30,000 digesters installed and biogas policy programmes [6].

The BioCool project aimed to combine the local access to the AD technology and the vast reserves of cattle manure arising from the growing numbers of cattle in Uganda, to pilot a biomethane-powered off-grid cooling innovation. BioCool piloted innovations to improve biogas production of existing traditional dome-type digesters in Uganda and use the recovered gas to directly power a refrigerator, without connection to electricity or the intermediate conversion of the biogas to electricity. The project pioneered an innovative Energy-as-a-Service (EaaS) tool for efficient user-defined cost assessment of biogas-powered cooling compared with traditional diesel-powered cooling to inform data-driven decision making. The BioCool innovation offers a sustainable and cost-effective solution for off-grid clean cooling supply for improved dairy productivity.

2. Materials and Methods

BioCool involved an initial modification of existing fixed dome AD systems (being the most used in Uganda) for improved biogas production, followed by the redesign of the combustion unit of a refrigerator that runs on LPG to enable its use with biogas, assessment of the cooling rate of the biogas and development of an EaaS tool to enable efficient costing of biomethane-powered cooling access to enable data-driven decision making.

About 91.1% of digesters installed in Uganda are fixed dome [7] and were used in the BioCool innovation. A fixed dome digester is a permanent, but resilient, underground infrastructure built with bricks and mortar, which offers high durability and low maintenance costs [8]. Fixed domes are ideal for warm climates like Uganda, harnessing constant underground temperature. They have 'fixed volume'; therefore, as gas is produced, it exerts pressure on the slurry, forcing the slurry into an expansion chamber (smaller adjoining slurry holding tanks).

Traditional domes are designed with a direct connection of the gas outlet to the point of use, e.g., cooking. As the gas is used, the pressure in the dome drops, allowing a backflow of the slurry in the expansion chamber into the digester dome. Without an intermediate gas holding tank as in traditional systems, pressure from continuous gas production forces slurry out of the expansion chamber, causing incomplete digestion of the slurry and hence loss of biogas in the process. Furthermore, gas production during AD creates air pockets within the digester. Advanced AD systems incorporate motorised mixers to help release trapped gases to the headspace, maintain a uniform temperature, pH and optimised retention time [9]. However, fixed domes do not have mixers installed, and hence, are quite likely to have significant biogas losses as gas trapped within the slurry leaves the digester with the effluent. Therefore, BioCool trialled two modifications to the traditional fixed dome digester: installation of a mechanical stirrer to enable homogenisation of the content and release of trapped gases, and the connection of a gas bag to depressurise the digester, allowing longer solids retention in the digester and consequently, more biogas recovery. The efficiency of these modifications was measured by the volatile solids (VS) destroyed with and without the modifications and physical observation of effluent discharge.

2.1 BioCool Innovation Workflow

The BioCool innovation assay (Figure 1) consisted of a slurry mixing inlet tank, a 30 m^3 underground fixed dome digester modified with a manual stirrer, an expansion chamber with two effluent displacement tanks and a 120m^3 gas storage bag.

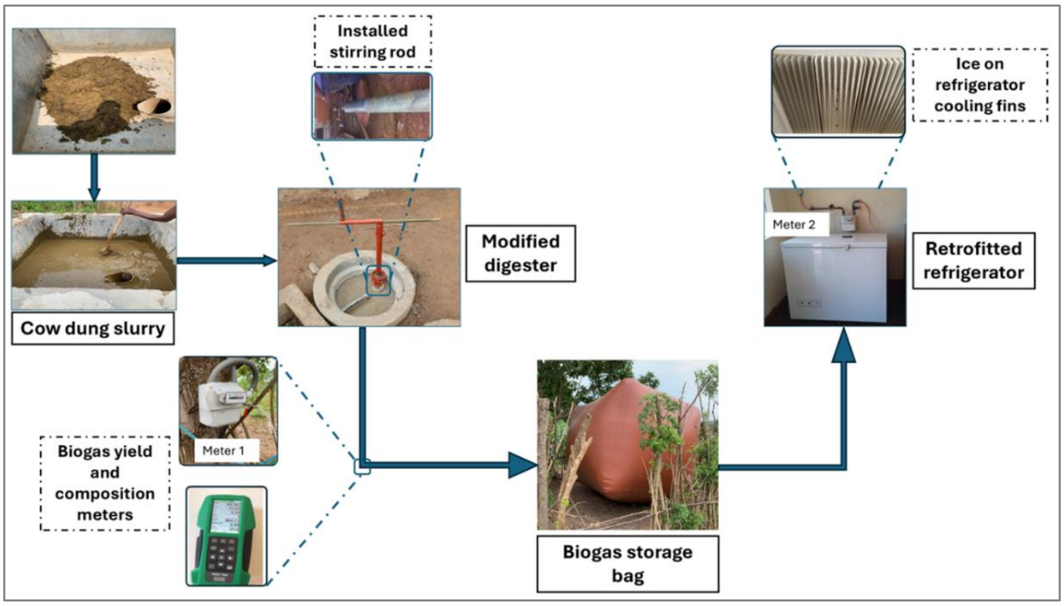


Figure 1. BioCool project workflow

The stirrer was made of hollow steel rods (as shown in Figure 1), anchored at the bottom and the top of the digester with ball rings to enable stability and ease of rotation. A 10 mm diameter flexible rubber hose was used to transport the biogas from the digester to the storage bag and from the gas bag to the refrigerator. A digital gas meter with 2 dm^3 resolution (RONGXIN, China) was installed between the digester and the gas bag to measure daily gas production (Meter 1), and another was installed between the gas bag and the refrigerator to measure gas consumption (Meter 2). A gas release valve was installed at the gas meter points for safety control and biogas composition analysis using a handheld biogas analyser (RASI 700 EiUK), which provided CH_4, CO_2, oxygen (O_2), hydrogen sulphide (H_2S), nitrogen (N_2) and gross calorific value.

2.1.1 Digester operation

Fresh cow dung was obtained from households with dairy farms in Mpigi, Uganda. Grass stalks and other debris were carefully removed from the fresh cow dung before transferring them to the inlet tank, where they were mixed with water in a ratio of 1:2 (1kg of cow dung to 2L of water) and stirred until all the solid lumps of dung were crushed and homogeneous and then fed into the digester dome. At first loading, the slurry was introduced into the digester until it reached the bottom level of the expansion chamber and then allowed for 20 days for microbial acclimatisation. After the acclimatisation period, the digester was run for a total of 80 days at a 20-day hydraulic retention time (HRT), fed daily with cow dung slurry (120kg of cow dung mixed with 240L of water). From days 0 – 20 (after the acclimatisation period), the digester was operated without stirring and was not connected to the external storage bag. During this period, the gas production and composition were measured once daily by opening the gas outlet valve. From days 21 – 80, the digestate was operated with daily mixing, by manually rotating the stirrer for five full revolutions, repeated up to three times daily. During this period, the gas outlet valve remained open, enabling a continuous gas flow into the storage bag. Samples of the fresh dung, mixed dung (fed slurry) and digestate (collected from the expansion chamber) were characterised for volatile solids (VS) twice per week, according to standard gravimetric methods [10].

2.1.2 Biomethane-powered cooling

The combustion unit of a refrigerator designed to run on LPG was modified to run on biogas. LPG has a higher energy density of 46 – 50 megajoules per kilogram (MJ/kg) compared to biogas with an energy density of around 20 – 25 MJ/m^3. To produce the same ignition/combustion capacity of LPG, a larger amount of biogas is required. Therefore, the combustion unit of the refrigerator was modified to maintain a higher supply of biogas than the original design. A water-resistant data logger (MX2202-70.140) was placed inside the refrigerator to measure time series (hourly) temperature data for three months. The logged data were retrieved and imported into the R software version 4.4.2, which was used to visualise the variation of temperature inside the refrigerator.

2.1.3 EaaS design based on multicriteria analysis

Although Uganda is one of the leading countries in SSA leading AD exploitation for clean cooking and lighting, techno-economic issues like insufficient feedstock supply and operating/maintenance know-how by rural households limit its long-term application and widespread adoption. BioCool project piloted an EaaS business model that transfers the techno-economic burdens of operating a digester to the energy provider, so that customers only pay for the fuel consumed or cooling service. This will enable more access to reliable, affordable and low-carbon fuel and improve livelihoods among the rural population. The EaaS was supported by a web-based tool developed to conduct a multicriteria analysis for biogas assessment to determine the most suitable sites for installing commercial biogas digesters, enabling potential biogas users to conduct self-assessments and make informed decisions regarding EaaS for cooling. Analysing key factors such as feedstock availability (organic waste), water access, and demand for biomethane applications, it provides data-driven guidance for optimising installation locations. Furthermore, the BioCool team conducted a thorough analysis of the current operational practices of MCCs in Uganda to enable a cost-benefit analysis for a switch from diesel to biomethane based on the EaaS model. Field visits were made to six bulk MCCs, including Nyakarongo Dairy Farmer Co-operative in Nakaseke District, Nabiswera Livestock Co-operative in Nakasongola District, Kyabareesa Farmers' Co-operative in Sembabule District, Kinyogoga Co-operative and Kijjumba Farmers' Co-operative in Nakaseke District, and Kabareekera Farmers' Co-operative in Sembabule District.

3. Results

3.1. Assessment of the efficiency of AD modifications

The average cumulative methane yield without mixing was 34.57 m^3 and 44.34 m^3 over 20-day HRTs with mixing, indicating a volumetric increase of up to 28.26% (Figure 2a). In agreement, intermittent mixing was reported to increase biogas by up to 70% due to increased gas mass transfer from the liquid phase to the gas phase [11]. The daily biogas quality without mixing (Figure 2b) had a relatively steady profile, while multiple peaks can be observed with mixing, believed to result from the occasional release of trapped gas when the digester content is mixed. Notwithstanding, the overall quality remained relatively similar with and without mixing, with CH_4 content ranging between 52.0% and 56.6%, and CO_2 content between 42.6% and 46.7% (Figure 2b).

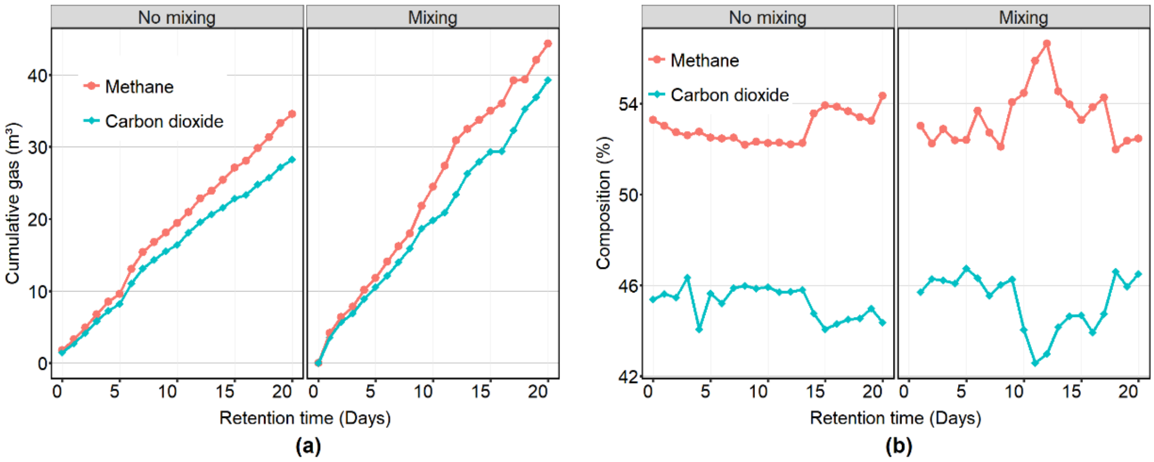


Figure 2. Biogas production (a) and composition (b) with and without mixing and external gas storage. The data for mixing are presented as the daily average over three sets of 20-day HRT mixing tests.

VS destruction presented in Figure 3 indicates the amount of organic material converted to biogas. The blue dots in Figure 3 represent the VS analytical points, and the dashed blue line indicates the average values. The VS data without mixing were from a household digester in Lusanja, where the cow dung used in the BioCool pilot was collected, and operational insights were applied in the digester operation at Mpigi to enable stakeholder engagement and data comparison with real-life application. Without mixing and a biogas storage bag installed, only 4% change in VS was observed between the digestate and the mixed cow dung fed into the digester (represented by the red arrows in Figure 3). This means that most of the materials left the digester without optimal biogas recovery. By implication, the unrecovered biogas is released to the atmosphere along with the digestate.

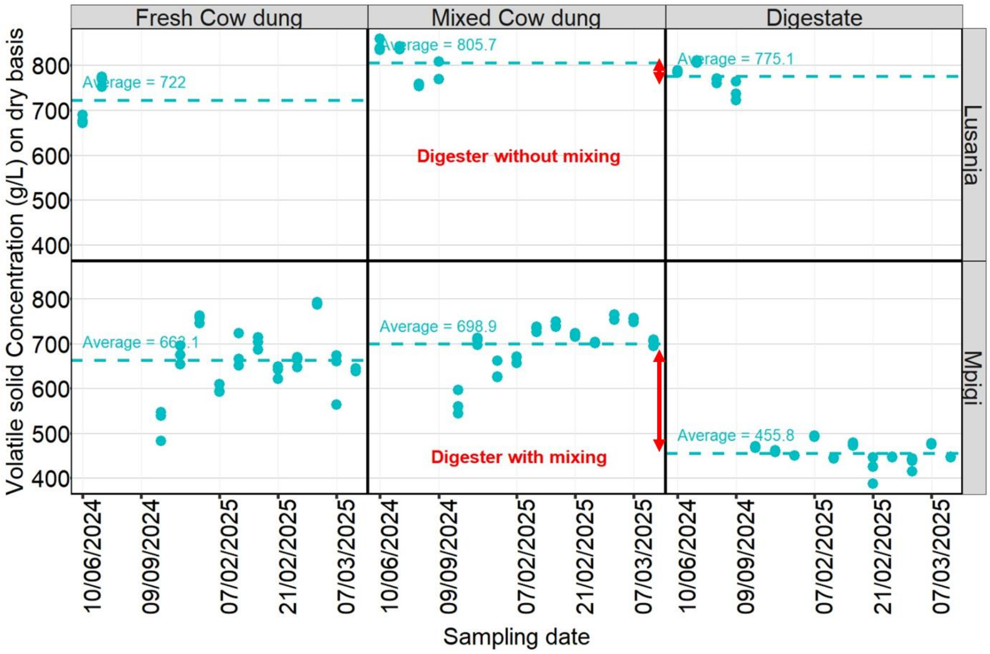


Figure 3: VS concentration: the top graphs represent data from the

However, with scheduled mixing and the installation of a gas bag, VS decomposition significantly increases to 35%, enabling a more efficient and climate-resilient biogas capture. While the overall biogas quality did not change with mixing and storage bag installation, the decomposition matrix significantly improved, thus allowing for potentially more methane recovery from the cow dung.

3.2 Cooling Curve

As shown in Figure 4, the direct use of biogas in the modified refrigerator enabled cooling down to a temperature of -6 °C. Due to the capacity of the data logger's capacity, it had to be removed from the refrigerator at certain intervals for data extraction and calibration. Furthermore, the refrigerator was loaded and in use during the pilot to simulate a real-life situation. Therefore, the high temperature spikes observed in Figure 4 indicate the ambient (room) temperature when the temperature logger was removed from the refrigerator for data extraction and recalibration, and/or when opened for use. Analysis of biogas consumption per unit change in temperature was limited to temperature datapoints ≤ 4 °C, being the target temperature for milk preservation in Uganda.

Interestingly, the temperature profile below the 4 °C temperature presents a wavelike pattern (Figure 4), believed to result from the composition of the biogas supplied for cooling (Figure 5). Biogas was supplied directly from the gas storage bag without an electric pump to deliver a steady gas flow rate. Therefore, the biogas supply to the refrigerator was a function of the excess pressure (with the gas bag in full capacity) resulting from the daily gas production.

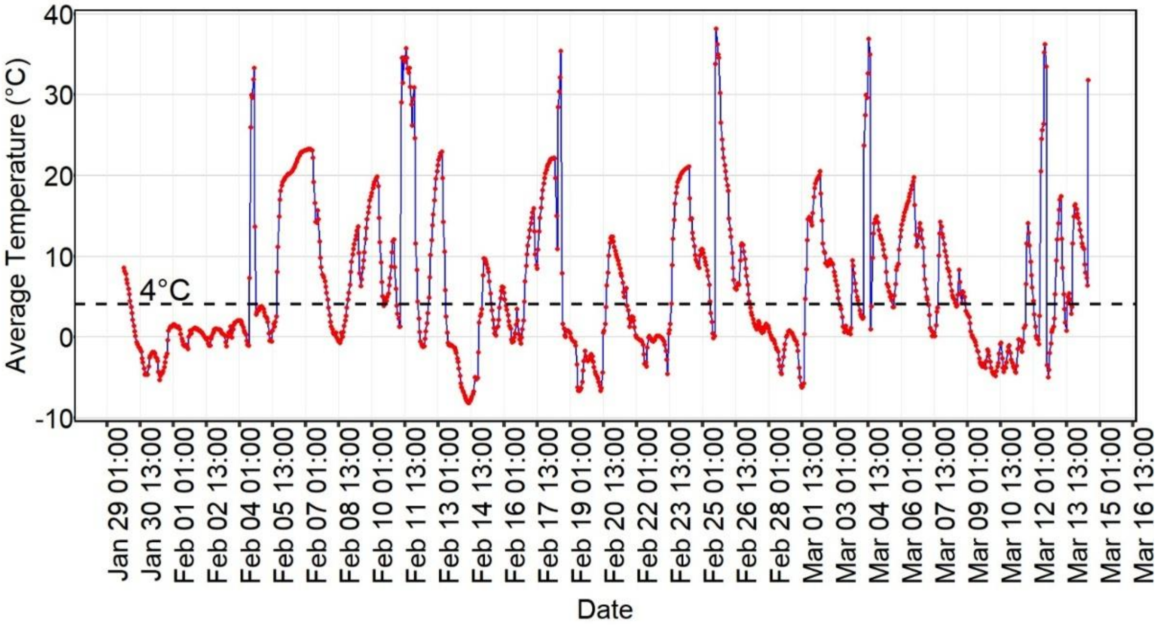


Figure 4. Biogas-powered cooling curve

The daily fluctuations in the composition of biogas supplied to the refrigerator (Figure 5) indicate inconsistencies in the amount of biomethane delivered daily to the cooling unit, and consequently, the biogas energy yield. These fluctuations might be responsible for the observed wavelike pattern of the cooling temperature under 4 °C in Figure 4 and not a steady-state profile.

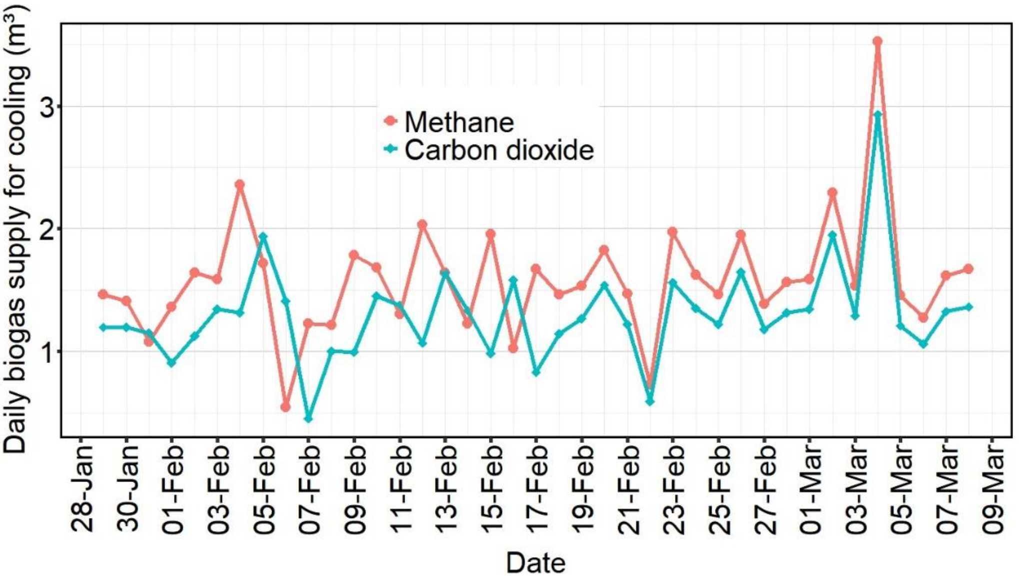


Figure 5. Composition of biogas utilised for cooling.

Based on the biogas production and composition analysis, the average biomethane yield over the 60-day cooling period was 1.87 ± 0.84 m^3/d, while 1.46 ± 0.75 m^3/d was utilised to achieve the lowest cooling temperature of -6 ˚C. Therefore, the amount of biomethane required to maintain a milk cooling temperature of 4 ˚C was calculated using equation 1.

$$Biomethane\ required\ to\ achieve\ 4℃ = \frac{Gas\ consumed\ to\ achieve - 6\ ℃}{Temperature\ change\ to\ achieve\ 4℃} \quad 1$$

Based on equation 1, an average of 0.146 m^3 of biomethane will be required daily to deliver milk cooling at 4 ˚C, which is equivalent to 7.7% of the average daily biomethane yield. This demonstrates that the BioCool innovation can become the game-changer technology to advance off-grid milk cooling in Uganda and across SSA.

3.3 EaaS Model Development and Assessment

3.3.1 Field visits to MCCs

MCCs are a critical component of the dairy value chain, ensuring the safe, hygienic, and efficient handling of milk from smallholder farmers to processors. Visits to MCCs across Uganda allowed the BioCool team to gain firsthand insights into the operational challenges and opportunities for improving energy efficiency. A key finding was that diesel is the predominant fuel used in these operations, powering the milk cooling systems across various dairy cooperatives. Milk coolers in use range in capacity from 5,000 to 10,000 litres, with smaller units being especially useful at the farm level. As part of the BioCool project, 15 MCCs were assessed, each equipped with milk cooling infrastructure to maintain milk quality and reduce spoilage before transportation (see Table 1).

Table 1. Operating data of MCCs visited

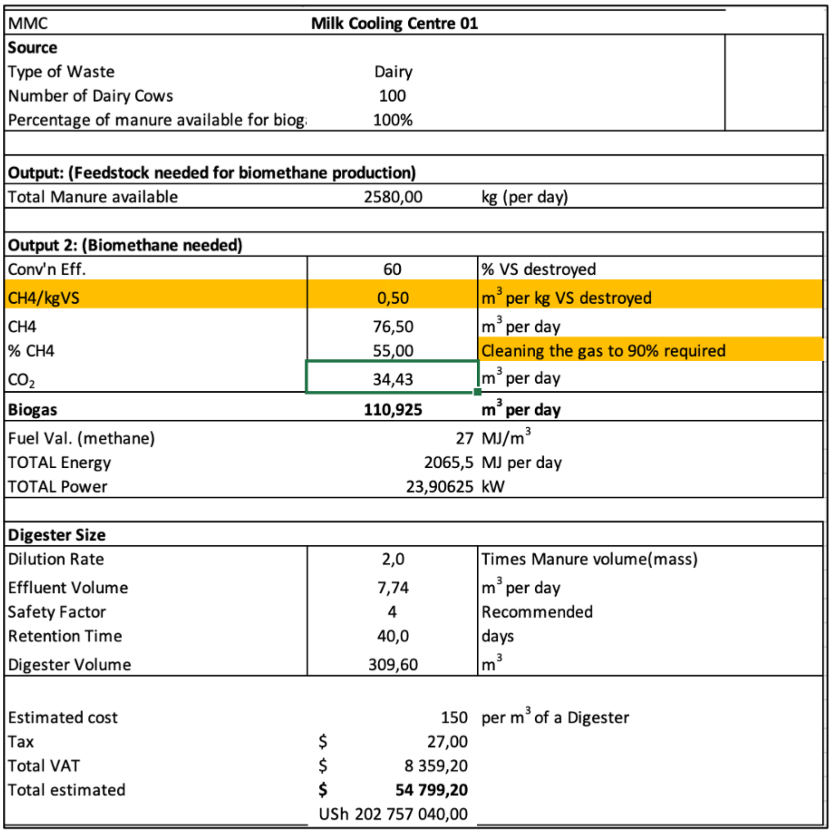
Milk cooling centre (MCC)	Capacity of the cooler	Average Diesel (litres)	Operating time	Average cost per month	
				USD($)	UGX
MCC 1	5000	20	8 am – 2 pm	825	3000000
MCC 2	5000	21	8 am – 2 pm	825	3000000
MCC 3	5000	22	8 am – 2 pm	825	3000000
MCC 4	5000	20	8 am – 2 pm	825	3000000
MCC 5	5000	20	8 am – 2 pm	825	3000000
MCC 6	5000	20	8 am – 2 pm	825	3000000
MCC 7	5000	20	8 am – 2 pm	825	3000000
MCC 8	5000	20	8 am – 2 pm	825	3000000
MCC 9	5000	20	8 am – 2 pm	825	3000000
MCC 10	5000	20	8 am – 2 pm	825	3000000
MCC 11	5000	20	8 am – 2 pm	825	3000000
MCC 12	5000	20	8 am – 2 pm	825	3000000
MCC 13	5000	20	8 am – 2 pm	825	3000000
MCC 14	10000	30	8 am – 2 pm	1200	4440000
MCC 15	10000	40	8 am – 2 pm	2000	7400000

Most of these centres (MCC 1 to MCC 13) are fitted with 5,000-litre milk coolers, while MCC 14 and MCC 15 are larger, each with a 10,000-litre capacity to support higher milk volumes from surrounding communities. All MCCs operate daily from 8:00 AM to 2:00 PM, aligning with peak morning milk deliveries. However, there is potential to extend operations beyond the current six-hour window to accommodate evening milk collections, which would enhance milk intake and farmer earnings. Cooling systems at these centres are powered by diesel generators, typically running for four hours per day. Diesel consumption ranges from 20 to 40 litres daily, depending on the cooler size and operational demands. Monthly operational costs are relatively uniform across the smaller centres, averaging $825 (UGX 3,052,500). In contrast, the larger MCCs incur higher expenses, $1,200 (UGX 4,440,000) for MCC 14 and $2,000 (UGX 7,400,000) for MCC 15, due to their greater energy requirements and scale of operations.

The current MCC's business model involves bulking milk, providing cold storage, and selling it to larger processors. While detailed revenue structures were not disclosed, MCCs typically earn a commission or fee per litre of milk stored. Notably, farmers do not pay in cash but contribute a portion of their milk as payment, creating a mutually beneficial system that supports both operational sustainability and farmer participation.

3.3.2 EaaS Business Model based on the biomethane assessment web tool

The biomethane assessment web tool (Link) was designed to evaluate and quantify the potential of organic resources for biomethane production. This will enable users to identify where feedstock is abundant, supporting data-driven decisions on optimal locations for installing AD systems.



MMC	Milk Cooling Centre 01	
Source		
Type of Waste	Dairy	
Number of Dairy Cows	100	
Percentage of manure available for biog	100%	
Output: (Feedstock needed for biomethane production)		
Total Manure available	2580,00	kg (per day)
Output 2: (Biomethane needed)		
Conv'n Eff.	60	% VS destroyed
CH4/kgVS	0,50	m^3 per kg VS destroyed
CH4	76,50	m^3 per day
% CH4	55,00	Cleaning the gas to 90% required
CO_2	34,43	m^3 per day
Biogas	**110,925**	**m^3 per day**
Fuel Val. (methane)	27	MJ/m^3
TOTAL Energy	2065,5	MJ per day
TOTAL Power	23,90625	kW
Digester Size		
Dilution Rate	2,0	Times Manure volume(mass)
Effluent Volume	7,74	m^3 per day
Safety Factor	4	Recommended
Retention Time	40,0	days
Digester Volume	309,60	m^3
Estimated cost	150	per m^3 of a Digester
Tax	$ 27,00	
Total VAT	$ 8 359,20	
Total estimated	**$ 54 799,20**	
	USh 202 757 040,00	

Figure 6. Sample output from the biomethane assessment web tool

By mapping resource availability geographically, the tool can help stakeholders prioritise sites with sufficient and reliable feedstock, improving project feasibility and long-term performance. These insights can then be linked to an EaaS model, where users pay for the energy produced rather than investing upfront in infrastructure. The BioCool EaaS business model offers MCCs access to clean, affordable, and reliable energy for milk cooling without any upfront capital investment. Instead of owning and managing the digester and cooling infrastructure, MCCs only pay a service fee based on the volume of biomethane consumed, similar to how they currently pay for diesel fuel. In this model, an Energy Service Company (ESCO) such as Green Heat takes full responsibility for designing, financing (ideally in partnership with financial institutions), installing, and operating a biomethane digester. The ESCO uses feedstock data to determine the appropriate size of the AD system. Based on this sizing, the required capital investment can be estimated and the expected biomethane production potential calculated. These projections are then applied to the EaaS pricing model, where tariffs are structured around the projected cubic meters of biomethane to be produced. This ensures that pricing reflects actual resource availability, system performance, and long-term operational viability.

In the case study assessment for MCC1 (Figure 6), to sustain daily operations, the digester requires approximately 2,500 – 3,000 kg of manure, which can be sourced from surrounding dairy farms or through urban waste management services. This amount of manure yields around 110 m^3 of raw biogas per day (based on the pilot study). After purification, i.e., removing CO_2 and other impurities that hinder cooling performance, approximately 76.5m^3 of high-quality biomethane is produced daily. Under the EaaS model, the biomethane is sold to MCCs at a fixed rate of UGX 1,500 per cubic meter. This translates to a daily energy cost of UGX 114,750, or about UGX 3.4 million (roughly $900) per month. These payments form the ESCO's revenue stream, enabling recovery of the UGX 202 million (approximately $55,000) capital investment while covering ongoing operational and maintenance costs. The cost per cubic meter of biomethane could be significantly reduced by constructing a larger-scale digester capable of processing 5-10 tonnes of manure daily. This would allow the production of biomethane at scale, enabling distribution across multiple MCCs and improving overall energy efficiency. Such an approach could lower unit costs through economies of scale. However, this opportunity requires further technical and economic feasibility studies to assess infrastructure needs, logistics, and potential partnerships for implementation.

Currently, MCCs spend about UGX 3 million ($825) per month on diesel for 4-5 hours of cooling per day (Table 1). Extending cooling to 10-12 hours using diesel would raise monthly costs to UGX 7.32 million. In contrast, the biomethane-based EaaS model supports extended cooling hours at a significantly lower cost, resulting in monthly savings of over UGX 3.92 million ($1,059). Beyond cost savings, this model enhances milk quality preservation, reduces post-harvest losses, and supports environmental sustainability by replacing fossil fuels with renewable energy. It also creates a circular economy by turning agricultural waste into a valuable energy resource, benefiting both MCCs and the wider dairy ecosystem. The EaaS model presents significant opportunities beyond energy provision. By utilising manure as a feedstock, the model enables additional revenue streams through the sale of dried slurry as organic fertiliser, the generation of carbon credits, and eligibility for climate finance mechanisms. These co-benefits not only enhance the environmental sustainability of the system but also strengthen its financial viability. Monetising these by-products can improve return on investment for the ESCO and create added value for participating farmers, making the business case for biomethane-powered cooling even more compelling and resilient in the long term.

4. Discussion

The EaaS model piloted under the BioCool project demonstrates a potential for a widespread application of off-grid biomethane-powered cold storage systems through simple modifications. Based on the average cumulative biogas production and VS destruction from the pilot scale study, intermittent mixing improved the AD performance compared to the non-mixed system, owing to increased gas mass transfer from the liquid phase to the gas phase. Several studies have reported the effect of mixing on AD and biogas production, with most of the studies being carried out on the lab-scale level. [12] investigated the effect of mixing on the AD of manure on lab-scale and pilot-scale experiments at 55 ^{0}C. They reported that the pilot-scale studies supported the lab-scale results with an average 7% increase in biogas yields during intermittent mixing compared to continuous mixing. The improved biogas production under intermittent mixing compared to continuous mixing in the pilot-scale plant was attributed to better solids and biomass retention in the reactor. Furthermore, [13] observed that intermittent mixing yields more biogas than continuous mixing at the beginning of the digestion process and varies after acclimation. Therefore, the increase in biomethane yield with the manual intermittent mixing applied in the BioCool project can be attributed to increased gas mass transfer and also a reduction in the settling of the solids inside the digester. Furthermore, the incorporation of a storage bag suggests a longer solids retention time in the digester, enabling more biomethane recovery.

The improvement in biomethane yield from traditional dome-type digesters in Uganda can support additional value creation beyond its current application for cooking. Based on the data from the biomethane-powered cooling technology piloted in the BioCool project, cooling was continuously achieved at -6 °C with the direct supply of biogas to the modified LPG refrigerator. To maintain a 4 °C temperature needed for milk cooling, only 7.7% of the biomethane produced would be consumed, leaving over 90% of the biomethane to continue to contribute to clean cooking. This disallows conflicting end-use demands for biomethane. Using the EaaS model developed, biomethane-powered off-grid cooling services can be efficiently costed to meet users' needs. This tool will help to streamline the decision-making process by providing clear, data-driven insights into the feasibility and benefits of digester installations, guiding both individuals and businesses in their energy investments.

Future works will focus on making the off-grid cooling technology affordable to smallholder farmers and households by utilising locally available resources to develop a holistic cooling infrastructure instead of modifying commercial products.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
EaaS	Energy-as-a-Service
LPG	Liquefied Petroleum Gas
GDP	Gross Domestic Product
MCCs	Milk Cooling Centres
SSA	Sub-Saharan Africa
HRT	Hydraulic Retention Time
VS	Volatile Solids
ESCO	Energy Service Company

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