Output 5: Technoeconomic Analysis of Low-Tech Biogasification Plants in Tanzania

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1. Background

This report was developed as part of the UN Climate Technology Centre and Network (CTCN) technical assistance delivered through pro-bono support by Inha University with funding from the government of Republic of Korea. The request for technical assistance was submitted by Nelson Mandela Institute through the Tanzania Commission for Science and Technology (National Designated Entity). The purpose of this report is a techno-economic analysis of biogasfication plants in Tanzania. Tanzania possesses extensive history with small domestic biogas digesters with volumes ranging from 6 – 13 m^3. These household units, constructed for domestic usage purposes such as cooking, laundry and heating, had construction costs ranging from 400-900 USD. Such reduction of construction cost was possible with local sourcing of materials and provision of labor from users themselves. However, these low-tech household biogas production units are mostly stopped due to lack of trained personnel and poor maintenance. The retrofitting conducted by the Korean experts in Tanzania didn't require a high level of technological retrofitting as removal of fixed slurry and sensor installation was the key component to increase the biogas production fourfold. However, building a sustainable logistical system, supply chain and end-user integration still remains a challenge.

2. Scope

The scope of this document includes three parts. The first part concerns the mapping of biogas plants in Tanzania at different scales. The second part discusses different biogasification technologies and their suitability and scalability in Tanzania. Lastly, different configuration of biogasification plants in Tanzania were analyzed financially and technologically.

3. Types of biogas plants in Tanzania

The heating of homes and kitchen stoves predominantly is done with biomass as primary fuel. Biomass such as firewood is used by over 60-70% of households nationwide. While having the benefit of being easily obtainable and used, it leads to environmental impacts such as deforestation, carbon emissions and health risks such as indoor air pollution resulting in respiratory diseases. Consequently, household-scale biogas plants were introduced to replace the usage of biomass in heating and cooking. Such biogas plants, which are based on an anaerobic digestion process, take in two to three cow's worth of manure and generate 1.5 – 2.5 m^3 of biogas every day. The biogas contains 60-70% methane, which can be combusted to be used for cooking and heating. The previous endeavor to install biogas plants in Tanzania were predominantly of household-scale. While household-scale biogas plants are manually operated and are suited to the end-user, the need for continuous operation and maintenance renders it difficult for these low-tech household-scale biogas plants to perpetuate. Thus, different scales and respective properties of biogas plants were investigated.

3.1. Household-Scale (4-13 m^3 digesters)

These serve single families, typically in rural areas. They are constructed to handle manure from 2 – 4 cows and produce low concentration and quantity of biogas enough for cooking and basic lighting. These household units are often incredibly simple in their design and rely entirely on manual laborer of the end user. From previous Official Development Assistance (ODA) projects, thousands of household units have been installed in Tanzania.

3.2. Medium-Scale (15-100 m^3 digesters)

These are medium sized biogas plants that can be installed in farms, schools or small businesses that produce tons of organic waste. These plants can take cattle manure from 10 – 50 herds and co-digest food waste or dairy waste producing enough biogas for communal kitchens, farm machinery or heating water. Medium-Scale biodigesters are precisely when waste supply management comes into play. A notable medium-scale biogas plant was built at a monastery in Mivumoni, northeastern Tanzania. This plug-flow configuration has a 100 m^3 reactor volume and was designed to produce 100 – 150 m^3 of biogas every day.

3.3. Large-Scale (Bigger than 100 m^3)

These facilities collect organic waste from multiple institutions ranging from municipal food waste to large slaughterhouses and food processing factories. A large biogasification plant can produce thousands of cubic meters of biogas which can lead to industrial scale electricity generation. It is estimated that around 2,000 m^3 of biogas production could cover small cities in Tanzania such as Moshi, which has a population of 220,000. The biggest problem with large-scale biogasification plants is the requirement of advanced technology and management which is not yet standard in Tanzania

4. Biogasification technologies and scale suitability

4.1. Fixed dome reactors

This design features an underground brick or concrete digester with a fixed masonry dome that traps biogas. These style of biogasification reactors are also called Chinese-style or Centre for Agricultural Mechanization and Rural Technology (CAMARTEC) design. They have no moving parts which indicate that no electricity is needed for operation, can withstand 15-20 years of operation as materials that were used to build these reactors are durable, and low maintenance when they were properly built. They also retain heat well which means that reactors are kept at proper temperatures required for mesophilic anaerobic digestion. Fixed dome reactors are suitable for small-scale rural use, which is the reason they were by-far the most common reactor configurations from previous projects such as Tanzania Domestic Biogas Program.

4.2. Plug-flow reactors

This design typically consists of elongated tanks or channels in which feedstock moves slowly from the inlet to the outlet as new material is added continuously. They often have a rectangular tubular shape, but they can be accommodated onto the ground as they can be built as concrete trenches with a flexible cover that is connected to a flexible gas bag which collects methane almost like a balloon. The U-shaped plug-flow reactor at Mivumoni monastery was built to treat cow manure and crop waste. These reactor configurations have advantages in scale-up as they can be extended longer to increase size. Furthermore, they can tolerate thicker feedstock of higher total solids concentrations. However, the lack of mixing and difficulty in maintenance remains a key bottleneck. Due to these technical characteristics, they are considered as medium tech solutions suitable for medium-scale reactors.

4.3. Continuous stirred tank reactors (CSTR)

Being the most advanced and mechanized configuration, CSTR is a large above ground cylindrical tank that is equipped with mixers and heating coils. CSTR is the standard in industrial biogas plants in Europe, US and East Asia; however, it is not yet common in Tanzania.

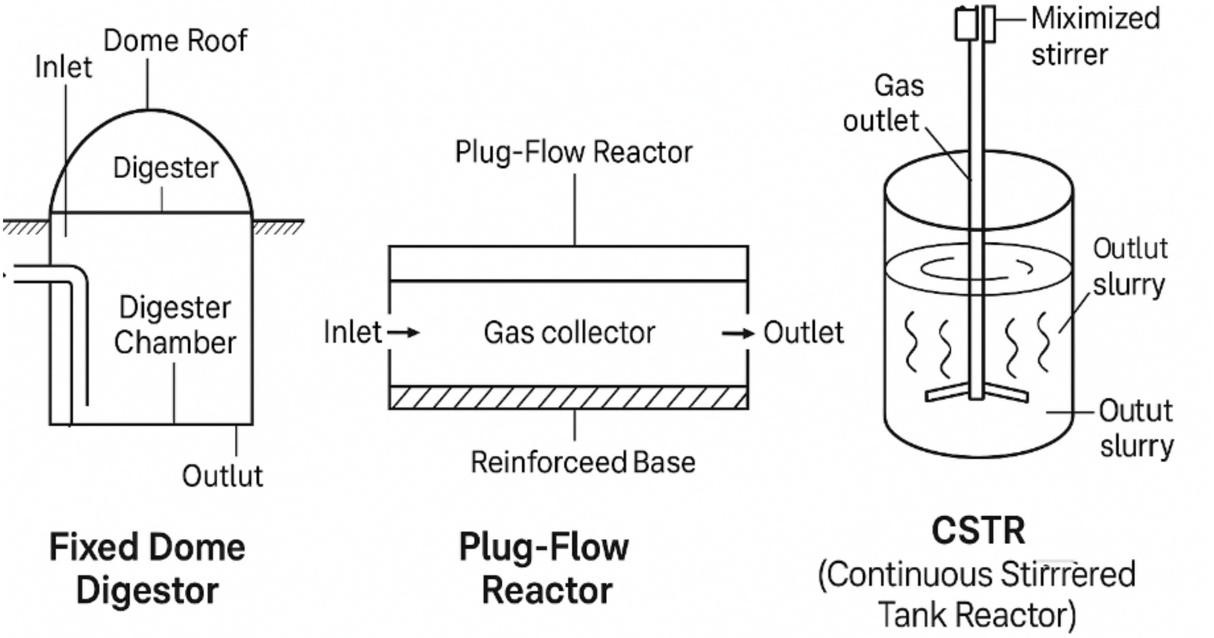

Fig. 1. Different types of biogas digesters.

5. Technological and financial analysis of biogas plants of different scales

5.1. Small, household-scale

Capital expenditure (CAPEX), the upfront cost for a small biogas unit in Tanzania ranges roughly from 600 – 900 USD. The reason why such low cost can be achieved was obtainment of local materials including bricks, cement, sand, gastight dome plaster, piping to kitchen and simple biogas burners. The employment of local labor for civil construction and piping also contributed to cost reduction. Depending on the region and construction variables, unit cost was from 100 – 200 USD/m^3.

$CAPEX=C_{equip}+C_{inst}+C_{eng}+C_{civil}+C_{cont}$

Where:

- C_{equip} : Equipment and machinery
- C_{inst} : Installation and integration
- C_{eng}: Engineering and design costs
- C_{civil} : Civil, structural, building works
- C_{cont}: Contingencies (often 10–30%)

$OPEX_{annual}=C_{labor}+C_{energy}+C_{maintenance}+C_{consumables}+C_{waste}+C_{admin}$

Where:

- C_{labor}: Labor and supervision
- C_{energy}: Electricity, fuel, gas
- $C_{maintenance}$: Spare parts, repairs
- $C_{consumables}$: Chemicals, additives
- C_{waste}: Sludge or byproduct disposal
- C_{admin}: Insurance, taxes, permits, admin overhead

$$ROI = \frac{Net\ Profit}{Total\ Investment} \times 100$$

$$ROI = \frac{(Revenue - OPEX_{annual}) \times N - CAPEX}{CAPEX} \times 100$$

N : Number of years in the analysis period

Net Profit = Total Return – Total Cost

Total Investment = CAPEX + cumulative OPEX (if needed for more complex models)

$$Payback\ Period = \frac{CAPEX}{Revenue - OPEX}$$

Operational expenditure (OPEX) for a household biogas unit is very low in monetary terms. This is due to operation being the responsibility of the end user. Labor is the main input. The household spends time daily collecting manure up to 150 kg/day, mixing it with water and feeding it to the digester. Periodical removal of internally accumulated slurry is also a responsibility of the end user. This can be considered as an opportunity cost, but without any salaries paid. Maintenance is also very minimal for these systems. There are no moving parts, so the only material that needs to be checked on a biannual basis is the pipes. The annual operation and maintenance costs are expected to be 10-20 USD. This only accounts for 2% of CAPEX excluding the non-monetized labor.

A well-maintained household unit produces around 2-4 m^3/day which can fuel 3-5 hours of cooking on a biogas stove replacing firewood and charcoal. These benefits translate into cost savings for the household. The annual profit a household can have with a well-maintained household unit is 80 – 120 USD. The payback period of these digesters is 8 – 12 years. However, the biggest problem with these optimistic statistics is that the digester must be properly maintained. As witnessed, these household units fail to operate because there is no supervision to operate these digesters. One of the most common reasons why these biogas digesters "die" is due to the accumulated slurry within the digester. The solution is to conduct internal cleaning every 6 months, but such maintenance is forgone, and biogas production is stopped. The de-centralized biogas digester operation of many non-skilled individuals is a logistical variable that can't be controlled.

5.2. Medium Scale

Medium-sized biogas digesters are often custom-built projects that has a very wide varying cost from 8,000 – 30,000 USD. These systems are considered medium tech, using plug-flow reactors, larger gas storage bags or multiple gas outlets and even a biogas generator if electricity and heat are to be produced internally. Economy of scale begins to appear as unit costs decrease to 80 – 150 USD/m^3. The Mivumoni plug-flow reactor with 100 m^3 size had an estimated cost of 200 USD/m^3 including imported materials which could be replaced by local materials, reducing the cost. However, medium sized reactors incur additional costs that small household reactors don't. These may include gas distribution piping, gas scrubber for H_2S reduction and larger slurry handling systems. These may add to CAPEX and increase the specific cost higher than the small-scale reactors.

Medium-scale digesters require more structured operation. If on a farm, the labor might be provided by farm workers who collect manure, mix and feed the digester daily – effectively a routine similar to managing manure pits. On a daily basis, tasks include feeding the substrate (which could be a few hundred kilograms for a 50 m^3 plant), checking that gas is flowing to appliances or engine, and occasional stirring if the design allows (some medium designs incorporate a manual or motorized stirrer in the inlet or a way to rod the digester). Labor cost may be significant if a dedicated operator is needed – for example, a school might assign a technician or a teacher to oversee the biogas system functioning. However, often these systems are managed as part of existing duties (e.g. farm staff). Maintenance needs to increase slightly at this scale: valves, gas hoses, and engines need periodic service. If a generator is run, engine oil changes and tune-ups are needed perhaps monthly. Operational expenses could include replacement of any broken gas plumbing parts, occasional repainting or rustproofing if there's a steel gas holder, and any fuel/electricity for auxiliary equipment (a medium digester usually still runs unheated, so no heating fuel needed; but a large mixer might consume a small amount of electricity if present). A medium plant might also eventually require periodic removal of sludge buildup (digester de-sludging every few years), which is labor-intensive but not usually a cash cost (the sludge is fertilizer). Water supply costs can grow for larger plants – e.g. a 50 m^3 digester might need hundreds of liters of water daily for mixing and cleaning, so if water must be pumped or purchased that adds cost.

However, medium biogas projects can achieve better financial metrics than household units, thanks to economies of scale and the possibility of revenue (or larger savings). A biogas plant using the cow manure could replace a portion of that energy. If a 50 m^3 digester yields ~25 m^3 biogas per day (assuming ~0.5 m^3 biogas per m^3 digester volume, with good feeding), that gas (equivalent 150 kWh energy) could produce perhaps 30–50 kWh of electricity per day or provide cooking fuel for dozens of people. Over a year, this might save on the order of 1,000–2,000 USD in energy bills (depending on what fuel is displaced – expensive diesel or cheaper alternatives). If properly sized so that the energy is effectively utilized, payback times of 5–8 years are feasible, and sometimes shorter if displacing expensive fuels. For instance, a farm that offsets diesel usage might see a high return on investment (ROI) because diesel costs in Tanzania can be substantial. On the other hand, if biogas only offsets cheap firewood, the monetary savings are less. The key to success for medium-sized digesters is to have dedicated management to realize energy generation, driving the ROI.

5.3. Large-scale

The CAPEX for large-scale installations can range from tens of thousands to millions of USD, depending on scale and sophistication. As a rough ballpark, a 500 m^3 plant might cost on the order of 50,000–100,000 USD to construct (if using mostly local materials for digesters and basic equipment), whereas a truly large project (2000–3000 m^3 across multiple tanks) with full power generation and gas cleaning could run into a few million USD with international-grade technology. Economies of scale do flatten out at very large sizes – additional volume still adds cost, but the per-unit volume cost can dip to 50– 80 USD/m^3. For example, the expected cost for ~2000 m^3 of digesters for Moshi's city waste project would likely be in the low hundreds of thousands of dollars (the study implies it's feasible but notes that such technology is not yet standard locally).

In another analysis, using a 100 m^3 digester with a generator, researchers estimated <200 USD per m^3 of capacity and anticipated a quick payback, suggesting an investment around 20,000 USD for the digester system that could support a generator

Scaling that up, multiple 100 m^3 modules or a single 500 m^3 tank plus equipment might be a few hundred thousand dollars including power generation units. Key cost components for large plants include civil works (multiple concrete digesters or a large, engineered lagoon), gas storage (large gas holder or multiple balloons), biogas utilization equipment (biogas gensets for electricity, or upgrading equipment if making biomethane, or boilers for heat), auxiliary systems (feedstock handling like shredders or pumps, digestate management like dewatering systems, H_2S scrubbers, flare for excess gas). There may also be costs for land, project development, and permitting. If foreign technology or engineers are involved, that can raise costs significantly compared to purely local construction.

The OPEX of these large-scale plants include the following: First, they typically employ full-time staff or trained operators. There will be at least an operator/technician overseeing feedstock loading, monitoring digester parameters (temperature, pH if measured, etc.), maintaining generators, etc. Labor costs in Tanzania for skilled technicians need to be considered (though lower than in developed countries, competent technical staff still come at a premium). Second, feedstock logistics become a major cost factor: transporting waste from collection points to the plant (fuel for trucks, drivers' wages) if the feedstock is not all on-site. For instance, a municipal plant needs a waste supply chain – potentially the city waste management would deliver organics, or the plant operator must pay to collect e.g. market wastes. Third, a large plant might use electricity for pumps, agitators, and control systems. Some of this can be self-supplied by the plant's own power, but during downtime grid or generator power might be needed. Water consumption could be high if processing solid waste (to maintain digesting moisture), though much water is recycled in the slurry. Lastly, maintenance including mixers, pumps, and engines require regular maintenance and occasional replacement. Gas engines running continuously require oil, filter changes, and overhauls. Digesters may need periodic dewatering of sludge (which requires equipment and labor). Any gas upgrading or scrubbing systems (e.g. iron sponge for H_2S removal, if used to protect engines) need media replacement or chemicals. All these contribute to ongoing OPEX.

Despite these costs, large plants also generate significant outputs that can offset expenses: namely electricity, heat, or biomethane that can be sold or used, as well as tipping fees for waste (in some models, a plant might be paid to take waste, as it provides waste treatment service). For example, if a large plant generates 300 kWh of electricity continuously, at a tariff of 0.10 USD/kWh, it grosses 720 USD/day (262,800 USD/year). Even after OPEX, this can yield a healthy profit if the plant is not too heavily financed. In Tanzania, feed-in tariffs or power purchase agreements for biogas power are not well-established, but an industrial plant could use all the power internally (displacing expensive diesel generation or unreliable grid supply). Additionally, the biofertilizer output from a large plant can be sold or used on farms, potentially adding revenue (though the market for bio-slurry fertilizer is still developing).

With the right conditions, large biogas projects can have strong financial metrics. The economies of scale often lead to lower cost per unit of energy produced, so if the energy has a buyer, the returns are attractive. A study from a pilot in Tanzania projected that a 100 m^3 plant producing electricity could recoup investment in as little as 3 – 6 years – corresponding to an ROI potentially in the 16–30% range depending on the scenario. At even larger scales (multi-hundred m^3), one could achieve ROIs above 15% if capital costs are kept in check and operations are efficient. Key to high ROI is high utilization of the biogas (idle or flared gas is lost revenue). For instance, running a generator at full capacity or supplying gas to an industrial boiler full-time will maximize income. If a plant is designed to produce more gas than gets used (common if initial plans overestimate demand), the ROI will suffer. However, the policies and incentives that play a crucial role in providing energy demand and subsidies to these industrial scale projects are almost non-existent in Tanzania.

Table 1. Financial analysis of biogasification plants of different scales.

Financial Metric	Household-Scale*	Medium-Scale**	Large-Scale***
CAPEX (USD)	600 – 900	8,000 – 30,000	50,000 – 100,000
OPEX (USD/year)	10 – 20	4,000 – 8,000	14,000 – 30,000
Biogas Production (NM3/year)	60 - 120	20,000 - 45,000	120,000 - 200,000
Revenue (USD/Year)	75 - 120	7,000 - 10,000	40,000 - 55,000
ROI (%)	8 – 10	12 – 20	16 – 30
Payback Period (Year)	10 – 12	5 – 8	3 – 6

* Revenue based on LPG or firewood replacement valued at \$0.08–\$0.12 per Nm^3.

** Processes 500–1,000 kg of feedstock per day with revenue estimated from energy sales, compost, and potential subsidies.

*** Monetized via electricity sales (\$0.06–\$0.10/kWh) or natural gas grid injection.

6. Conclusion

In the Tanzanian context, economies of scale in biogas are tempered by practical realities – feedstock availability, transport infrastructure, and local technical capacity. Thus, a balanced approach is needed: continue deploying many small biogas units where they directly improve lives and simultaneously build experience with larger installations through pilot projects (as has been done in Arusha and Tanga regions). Over time, as local expertise grows and success stories accumulate, financing larger biogas ventures will become easier and the technology can be scaled up to its full potential, from village to city. For example, a more detailed methodology to evaluate the optimal location for large, industrial biogasification plant would include several factors including waste availability such as livestock manure and agricultural residue, logistics and infrastructure such as road access, proximity to electricity grid, transportation, electricity demand, policy and support including local government subsidies and water availability. Detailed assessment of these factors included within the business proposal would render the project much more feasible and lucrative.

In summary, biogasification in Tanzania can be economically viable across scales when done correctly. Small, medium, and large biogas plants each have their niche: household systems provide decentralized energy access and environmental relief, mid-sized digesters serve farms/communities and can break even with careful use, and large plants promise city-wide waste-to-energy solutions with profitable returns. All scales contribute to sustainable development goals. By leveraging local strengths (like low-cost construction and available organic resources) and learning from past challenges (ensuring maintenance, matching supply and demand), Tanzania can expand biogas adoption. The techno-economic insights in this report should guide policymakers, investors, and development practitioners in designing biogas projects that are not only technically sound but also economically sustainable in the long run.