Biogas-Based Mini-Grids for Rural Communities: Energy Access and Environmental Benefits

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ABSTRACT

Rural electrification in Sub-Saharan Africa remains constrained by weak distribution infrastructure, high diesel logistics costs, and the limited ability of solar home systems to support productive loads. This paper examines biogas-based mini-grids as a dispatchable renewable option for rural communities with concentrated organic residues from livestock, markets, crop processing, and food waste. Unlike intermittent renewables, a properly sized anaerobic digestion plant can provide schedulable electricity while also producing digestate for agriculture and reducing uncontrolled organic waste decomposition. The paper develops a screening-level techno-environmental model for feedstock conversion, generator dispatch, reliability, and emissions accounting. An illustrative rural community case is used to show how biogas generation, modest battery storage, and demand-side prioritisation can support evening loads, small enterprises, water pumping, refrigeration, and institutional services. The results indicate that biogas mini-grids are most defensible where feedstock is local, collection is organised, methane leakage is monitored, and tariffs support professional maintenance. The conclusion is blunt: biogas is not a magic rural energy solution, but in the right agricultural and peri-urban waste contexts, it can provide a serious low-carbon alternative to diesel mini-grids.

Keywords: anaerobic digestion; biogas; rural electrification; mini-grids; methane leakage; digestate; energy access; Sub-Saharan Africa.

INTRODUCTION

Electricity access remains one of the clearest technical and social bottlenecks in rural development. The 2025 SDG7 progress assessment reports that more than 666 million people still lack access to electricity, with Sub-Saharan Africa accounting for the largest share of the access deficit [1]. At the same time, the clean-cooking problem is even larger: the International Energy Agency estimated that about 970 million Africans lacked access to clean cooking in the early 2020s [2]. These numbers are not decorations for an introduction; they define the engineering problem. Rural communities need electricity that is not merely symbolic but sufficient for lighting, phone charging, milling, irrigation, refrigeration, clinics, schools, small workshops, and digital services.

Solar photovoltaic mini-grids have rightly received strong policy and investor attention. However, renewable-rich rural systems still face evening peaks, seasonal resource variability, limited affordability, and weak development of productive loads. Diesel generators remain common because they are dispatchable, familiar, and easy to size, although fuel logistics and emissions make them expensive and environmentally undesirable. Biogas-based mini-grids occupy a useful middle ground: they convert local organic residues into dispatchable electricity, with digestate returned to farms as a nutrient source.

The relevant policy question is whether biogas can be engineered into a reliable, maintainable and financially viable rural electricity service. World Bank and ESMAP work on mini-grids stresses regulation, finance, productive use and operations [3]. Biogas contributes only where feedstock density, water availability, operator competence, tariff collection and environmental controls are adequate.

This paper contributes a compact framework for evaluating biogas-based mini-grids for rural communities. It presents: (i) a technical architecture for community-scale systems; (ii) equations for feedstock-to-electricity conversion and dispatch; (iii) editable screening tables for feedstock, assumptions and results; and (iv) an implementation discussion focused on African rural contexts.

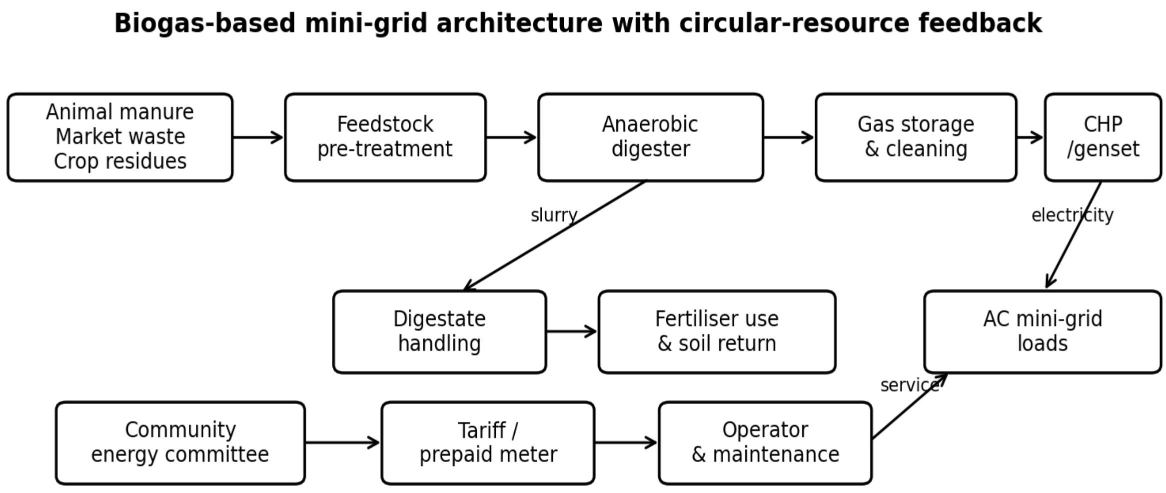

Figure 1. Biogas-based mini-grid architecture with feedstock, electricity and digestate loops.

TECHNICAL ARCHITECTURE OF A BIOGAS MINI-GRID

A community-scale biogas mini-grid normally contains six subsystems: feedstock collection, pre-treatment, anaerobic digestion, gas cleaning and storage, electricity conversion, and low-voltage distribution. Figure 1 shows the resource flow. Feedstock may include cattle manure, poultry litter, agro-processing residues, market waste and food-processing by-products. The engineering challenge is not simply methane production; it is reliable daily logistics. If the feedstock is dispersed, seasonal, contaminated with plastics, or socially contested, the plant will fail regardless of how elegant the design spreadsheet looks.

The anaerobic digester converts biodegradable volatile solids into biogas, typically a mixture dominated by methane and carbon dioxide. The gas is then dried and desulphurised before being fed to an internal combustion engine, microturbine, or combined heat and power unit. In rural African settings, the most realistic option is often a robust spark-ignition biogas genset with locally serviceable components. Batteries may be added to reduce start-stop cycling, absorb short disturbances, and improve evening reliability. Heat recovery is valuable when there are nearby thermal uses, but many rural electricity projects underuse heat because productive thermal loads are not planned at the outset.

Table 1 summarises feedstock options. These are not interchangeable commodities. Cattle manure is stable but has modest energy density; market waste has higher gas potential but requires sorting and contamination control; crop residues are seasonal and may already have competing uses as animal bedding, soil cover or fuel.

Table 1. Feedstock suitability for rural biogas mini-grids.

Feedstock	Main advantage	Main weakness	Mini-grid implication
Cattle manure	Predictable daily supply near livestock clusters	Low methane yield per kilogram and high water demand	Good anchor feedstock if animals are concentrated
Poultry litter	High organic content	Ammonia inhibition risk and odour management	Useful in blends, but needs careful process control
Market and food waste	High biogas potential and waste-management benefit	Plastic contamination and collection discipline	Attractive near trading centres and peri-urban villages

Crop residues	Locally available after harvest	Seasonal, bulky and often already used	Better as supplementary feedstock, not sole input
Agro-processing waste	Concentrated and easier to contract	Depends on local enterprise continuity	Strong option near mills, dairies, abattoirs or breweries

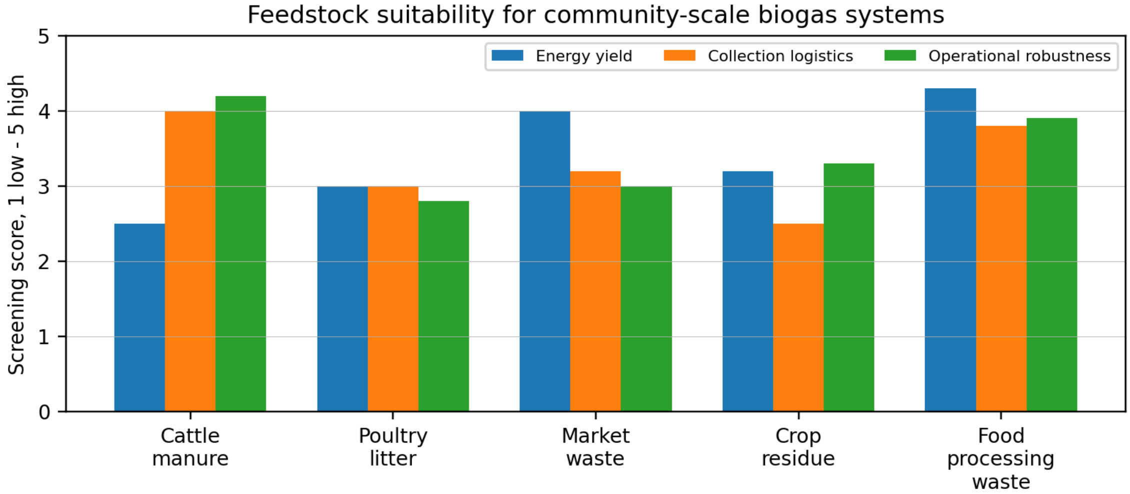

Figure 2. Feedstock suitability scores for energy yield, logistics and operational robustness.

SCREENING MODEL

A defensible first-pass model should connect organic feedstock to gas output, gas output to dispatchable electricity, and dispatchable electricity to reliability and environmental indicators. Let $i \in \mathcal{F}$ denote feedstock types and $t \in \mathcal{T}$ hourly periods. The daily biogas volume is approximated by

$$B_t = \sum_{i \in \mathcal{F}} M_{i,t} \ TS_i \ VS_i \ Y_i \ \eta_i^{AD}$$

where $M_{i,t}$ is wet feedstock mass, TS_i is total-solids fraction, VS_i is volatile-solids fraction, Y_i is specific biogas yield, and η_i^{AD} is the realised digestion efficiency. This equation is intentionally simple. A final design should use laboratory biochemical methane-potential data or locally calibrated pilot-plant data.

The useful electrical energy from the produced gas is estimated as

$$E_t^{el} = \eta^g \frac{x_{\mathrm{CH_4}} B_t \mathrm{LHV}_{\mathrm{CH_4}}}{3.6}$$

where η^g is generator efficiency, x_{CH_4} is methane fraction, and LHV_{CH_4} is the lower heating value of methane in MJ/m^3. The division by 3.6 converts MJ to kWh. A poor student would stop here and announce success; an engineer continues to reliability, storage and operations.

For each hour, the mini-grid power balance is

$$P_t^{bio} + P_t^{dis} + P_t^{pv} + U_t = D_t + P_t^{ch} + C_t$$

where P_t^{bio} is biogas generation, P_t^{dis} and P_t^{ch} are battery discharge and charge, P_t^{pv} is optional photovoltaic output, D_t is demand, U_t is unserved load, and C_t is curtailed or unused energy. For a pure biogas mini-grid, $Ptpv = 0$; it is retained in the equation because many practical projects hybridise biogas with PV.

Gas storage evolves according to

$$S_t^g = S_{t-1}^g + B_t - \frac{3.6P_t^{bio}}{\eta^g x_{\mathrm{CH_4}} \mathrm{LHV}_{\mathrm{CH_4}}}, \quad 0 \le S_t^g \le \overline{S}^g$$

And the battery state of charge follows

$$SOC_t = SOC_{t-1} + \eta^{ch} P_t^{ch} \Delta t - \frac{P_t^{dis} \Delta t}{\eta^{dis}}, \quad SOC^{min} \le SOC_t \le SOC^{max}.$$

Reliability is represented by expected energy not served and loss-of-power-supply probability:

$$\mathrm{ENS} = \sum_{t \in \mathcal{T}} U_t \, \Delta t, \qquad \mathrm{LPSP} = \frac{\sum_{t \in \mathcal{T}} U_t \, \Delta t}{\sum_{t \in \mathcal{T}} D_t \, \Delta t}.$$

The greenhouse gas accounting is expressed as

$$\Delta CO_{2e} = E^{\mathrm{served}} \mathrm{EF}^{\mathrm{diesel}} + A_{\mathrm{CH_4}}^{\mathrm{waste}} - \left(E^{\mathrm{served}} \mathrm{EF}_{\mathrm{aux}}^{\mathrm{bio}} + L^{\mathrm{CH_4}} \rho_{\mathrm{CH_4}} \mathrm{GWP}_{\mathrm{CH_4}} \right).$$

The first term is displaced diesel electricity; the second is avoided methane from unmanaged waste; the bracketed terms are auxiliary emissions and methane leakage from the biogas chain. This is the equation reviewers will attack first. They will be correct to do so if leakage, waste baseline, and digestate emissions are waived. Methane leakage is not a rounding error.

Finally, the levelised cost of electricity is

$$\mathrm{LCOE} = \frac{\mathrm{CRF} \cdot \mathrm{CAPEX} + \mathrm{OPEX}_f + \mathrm{OPEX}_v + C^{\mathrm{feedstock}}}{\sum_{t \in \mathcal{T}} E_t^{\mathrm{served}}}.$$

This formulation is adequate for screening. Bankable project development requires measured feedstock data, tariff willingness-to-pay surveys, protection studies, engine derating assumptions, spare-parts supply chains, and a maintenance plan.

ILLUSTRATIVE RURAL COMMUNITY CASE

Table 2 defines a stylised rural community. The assumptions are deliberately transparent and conservative. They are not field measurements and should not be cited as a national dataset.

Table 2. Screening assumptions for a stylised rural community.

Parameter	Assumed value	Rationale
Population served	900 people	Village-scale mini-grid with households and small enterprises
Connected customers	170 households, 18 businesses, 3 public facilities	Includes clinic, school and water point
Peak demand	48 kW	Evening residential peak plus small productive loads
Daily demand	505 kWh/day	Tier beyond basic lighting and phone charging
Available wet feedstock	2.4 t/day	Manure plus market and agro-processing residues
Average biogas production	240 m3/day	Screening value requiring local validation

Methane fraction	60%	Typical practical range for stable digestion
Genset rating	60 kW	Allows peak support without continuous full-load operation
Electrical efficiency	32%	Conservative small-genset assumption
Battery energy capacity	120 kWh	Smooths peaks and reduces engine cycling
Methane leakage case	2% of methane is produced	Target level requiring active leak detection
Diesel reference emission factor	0.80 kg CO2e/kWh	Screening value for small diesel generation

The dispatch concept is shown in Figure 3. The biogas genset provides schedulable energy, while the battery covers short evening deficits and reduces unserved energy. The important result is qualitative: biogas shifts the rural mini-grid discussion from weather-following generation alone to a fuel-logistics and waste-management problem. That is not easier, but it is more controllable when the community has reliable feedstock streams.

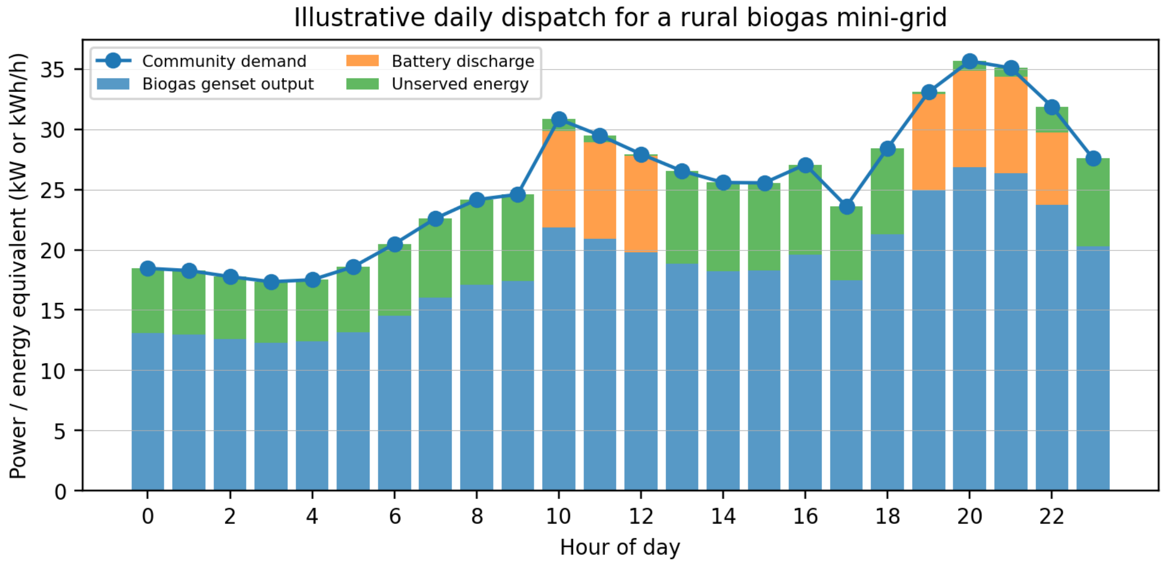

Figure 3. Illustrative daily dispatch for the biogas mini-grid.

Table 3 reports screening-level indicators. These values should be read as a design demonstration, not as experimental performance.

Table 3. Illustrative technical and environmental indicators.

Indicator	**Value**	**Interpretation**
Served electrical energy	470 kWh/day	Sufficient for lighting, refrigeration, water pumping and micro-enterprises
Energy not served	35 kWh/day	Remaining deficit concentrated at evening peak
LPSP	6.90%	Too high for a clinic-only feeder; acceptable only with prioritised critical loads
Average genset utilisation	31%	Indicates room for load growth or improved scheduling
Diesel reference emissions	390 kg CO2e/day	Baseline for equivalent small diesel supply
Biogas electricity-chain emissions	105 kg CO2e/day	Includes auxiliary energy and methane leakage case

Biogas with waste-management credit	55 kg CO2e/day	Assumes avoided unmanaged organic-waste methane
Indicative gross emission reduction	73%	Relative to the diesel reference, excluding waste credit
Critical implementation constraint	Feedstock governance	The project fails if the collection contracts fail

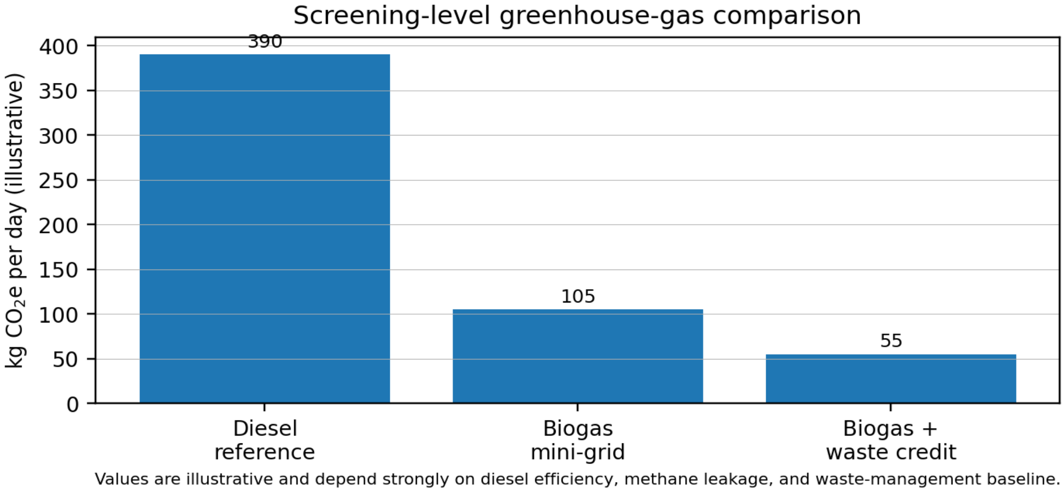

Figure 4. Screening-level greenhouse-gas comparison.

ENERGY ACCESS BENEFITS

The first benefit is dispatchability. A biogas genset can be scheduled for the evening peak, whereas a PV-only plant must rely heavily on batteries after sunset. This matters for shops, grinding mills, cold rooms, clinics and schools. A second benefit is compatibility with productive use. If agro-processing residues serve as feedstock, electricity can return to the same local value chain through milling, drying, refrigeration, and pumping. This circular relationship is more plausible than importing diesel into a village to power the processing of crops that also generate waste [11].

Third, biogas projects can support multi-vector energy access. Electricity is not the only useful output. Some communities may use gas directly for cooking or institutional thermal loads; others may prioritise electricity and use heat recovery for drying or water heating. However, designers must resist overpromising. A 50-kW-class plant cannot simultaneously electrify every household, replace all cooking fuels, run irrigation, power all businesses, and deliver high availability unless feedstock and capital are scaled accordingly.

Fourth, mini-grids can be designed around critical-load prioritisation. Clinics, vaccine refrigeration, water pumps, telecom towers and schools should be protected through feeder segmentation or smart metering. A rural power system that treats a phone charger and a vaccine refrigerator with the same priority is badly designed.

ENVIRONMENTAL BENEFITS AND RISKS

Waste-based biogas can reduce emissions through three mechanisms: displacement of diesel electricity, avoidance of uncontrolled methane from decomposing organic waste, and replacement of some synthetic fertiliser with digestate. IEA's biogas and biomethane assessment highlights the importance of feedstock-specific potential and proximity to infrastructure [4], while IRENA notes the continuing role of bioenergy within the renewable energy mix [5]. The environmental case is therefore credible, but conditional.

The main environmental risks are also clear. Methane leakage can undermine a large share of the climate benefit because methane has a high warming potential. Digestate can create odour, pathogen, and nutrient runoff problems if storage and land application are sloppy. Water demand may be non-trivial in dry communities. Competition for crop residues can undermine soil conservation. Purpose-grown energy crops should generally be avoided in food-insecure areas unless land-use impacts are rigorously assessed.

Table 4 summarises risks and mitigation measures. This is the table policymakers should read before approving subsidies.

Table 4. Implementation risks and mitigation measures.

Risk	Consequence	Mitigation
Feedstock shortfall	Low gas output and load shedding	Contract feedstock suppliers; diversify feedstock; establish weighing records
Methane leakage	Climate benefit collapses	Gas-tight construction; leak detection; maintenance incentives
Poor digestate MANAGEMENT	Odour, water pollution and community opposition	Covered storage; agronomic application plan; farmer training
Tariff under-recovery	Maintenance collapse	Cost-reflective lifeline tariff plus productive-use customers
Weak operator capacity	Downtime and unsafe operation	Local technician training; remote monitoring; spare-parts plan
Social exclusion	Benefits captured by large users	Community governance; critical-load protection; transparent connection rules
Seasonal feedstock variation	Reliability deterioration	Gas storage, feedstock blending, backup generation or hybrid PV/storage

DISCUSSION: WHEN IS BIOGAS THE RIGHT CHOICE?

Biogas mini-grids are strongest in communities with clustered livestock, markets, schools, clinics, agro-processing residues or food-processing facilities. They are weaker in dispersed settlements with low organic-waste density, little water, weak road access, and no institution capable of enforcing collection routines. This is why site selection matters more than public-relations language.

The technology is particularly relevant to agricultural belts, peri-urban markets and rural growth centres, where electricity demand and organic-waste generation coexist. Still, the project must be an electricity service business, not a digester demonstration. Tariffs, metering, protection settings, maintenance and customer management determine survival.

Hybridisation should be considered carefully. PV can reduce daytime biogas consumption and preserve gas for evening peaks. Batteries improve short-term reliability. Diesel backup may still be justified for emergency resilience, but should not become the dominant energy source. The resulting design problem is a mixed technical-economic optimisation problem involving feedstock availability, generation scheduling, reliability targets, emissions and affordability.

POLICY AND BUSINESS-MODEL IMPLICATIONS

A viable policy framework should support site screening, capital grants, concessional finance, productive-use loans, feedstock aggregation and environmental monitoring. Subsidy should not reward installed capacity alone. It should reward delivered service, verified uptime, useful energy consumption, methane leak control, and safe digestate reuse. Otherwise, the sector will repeat the familiar cycle: donor-funded installation, weak operation, poor revenue, no maintenance and eventual abandonment.

Three business models are plausible. The first is a community cooperative, suitable where governance is strong and demand is modest. The second is a private operator under a regulated concession, better suited where professional maintenance and metering are required. The third is an anchor-business model, in which an agro-processing facility, market, dairy cluster, or institution provides a stable revenue base. For most African rural settings, the anchor-business model is technically and financially more convincing than a purely household-load model.

LIMITATIONS AND RESEARCH REQUIREMENTS

This paper presents a screening framework, not a validated field trial. A serious follow-up study should add: measured feedstock quantities and biochemical methane potential; hourly demand surveys; geospatial collection-cost modelling; laboratory digestate analysis; gas-leak measurements; AC load-flow and protection studies; stochastic feedstock and demand scenarios; willingness-to-pay analysis; and comparison with PV-battery-diesel alternatives.

The most important research gap is not another generic claim that biogas is sustainable. The gap is in the integrated optimisation of feedstock logistics, digester sizing, gas storage, electricity dispatch, customer segmentation, emissions accounting, and tariff design. That is where a publishable contribution lies.

CONCLUSION

Biogas-based mini-grids can improve rural energy access while delivering environmental benefits through waste treatment, diesel displacement and nutrient recycling. Their value is highest where organic residues are concentrated, collection can be governed, and electricity demand includes productive and institutional loads. The proposed screening equations and an illustrative case show how feedstock conversion, dispatchability, reliability, and emissions can be evaluated within a single framework. The main conclusion is disciplined rather than romantic: biogas mini-grids are not universally appropriate, but in suitable rural communities they can become reliable low-carbon infrastructure rather than decorative development projects.

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