
SOLAR-BIOMASS HYBRID SYSTEMS FOR INTEGRATED LIVESTOCK-HORTICULTURE FARMS IN SUB-SAHARAN AFRICA: A REVIEW

Kouétcha Esaïe Kombetto^{1,*}, James Garba Ambafi¹, Taliha A. Folorunso¹

¹*Federal University of Technology Minna*

Email: kouetchaemen183@st.futminna.edu.ng, ambafi@futminna.edu.ng, funso.taliha@futminna.edu.ng

***Corresponding author:** Kouétcha Esaïe Kombetto

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Integrated livestock-horticulture farms in sub-Saharan Africa depend on costly diesel power while producing manure and crop residues whose energy value is rarely recovered. This review examines how photovoltaic generation and biomass conversion through anaerobic digestion or gasification can be combined into a single farm microgrid. A literature search conducted in Google Scholar on 1 September 2026, covering 2021–2026, returned 43 studies that met the inclusion criteria, 24 of them reporting sub-Saharan African sites or datasets. Every system-level result reported for a solar-biomass hybrid is a simulation. The pairing suits farm conditions: solar output serves daytime irrigation and processing loads, while biogas from on-farm waste provides dispatchable power for the evening peak and heat for brooding, sanitation and cooling. Reported hybrids deliver USD0.265/kWh against USD0.980/kWh for diesel at one Ghanaian site and cut operational CO₂ sharply: from 400 t/yr under a diesel-dominant configuration to 31.8 t/yr at the selected optimum for a Nigerian poultry facility, and from 636 t/yr under diesel-only supply to below 1 kg/yr at a Tanzanian village, all on a combustion-only boundary. Digestate returns to the cropped area as fertiliser. Three design lessons follow. Biogas delivers more value as heat than as electricity at farm scale, so the digester should be sized against thermal demand, allowing for the heat the fermenter consumes. Storage carries the largest share of lifetime cost, so scheduling shiftable loads into the solar window is the most rewarding control measure. Reported profiles, efficiencies and substrate properties vary with site and method, so local characterisation should precede sizing.

Keywords: solar-biomass hybrid systems; anaerobic digestion; farm microgrid; dispatch strategy; techno-economic analysis; sub-Saharan Africa

1. INTRODUCTION

Agriculture supports more than half the population of sub-Saharan Africa, smallholders account for roughly 80% of production and over 90% of cropland is rainfed, while about 75% of rural people and most rural enterprises lack reliable electricity (Falchetta *et al.*, 2023). Design practice compounds the deficit: rural generation studies address residential and institutional loads with little regard for productive uses, one Tanzanian village model entering agricultural demand as zero (Mwakitalima *et al.*, 2023) and Zambian fieldwork showing households acquiring capacity adequate for lighting but not income generation (Chanda *et al.*, 2026). Holdings combining livestock with horticulture fit neither template, yet are common: at Mankramso in Ghana, 89.8% of households farm crops and rear livestock (Odoi-Yorke, Abaase, *et al.*, 2022).

Where such holdings secure power off-grid it is predominantly diesel, consistently the costliest option: reviewed mini-grid studies place diesel at USD0.92–1.30/kWh (Zebra *et al.*, 2021), and community-scale examples reach USD0.980/kWh at Mankramso (Odoi-Yorke, Abaase, *et al.*, 2022). The environmental burden follows: at Abeokuta the diesel-containing optimum emits 31,840 kg of CO₂, against 15.8 kg for the diesel-free configuration retaining a 50 kW biomass generator (Emezirinwune *et al.*, 2024).

The resources to displace diesel are already on the holding. Photovoltaic pumping is economically feasible for smallholders at scale (Falchetta *et al.*, 2023), and biomass valorisation is a viable electrification route because agricultural and livestock waste accumulates wherever farming concentrates (Uzoagba *et al.*, 2024). Hybrids pairing renewables with storage or a dispatchable unit are

the established off-grid route (Zebra *et al.*, 2021), and solar-biomass suits farm conditions because photovoltaic output coincides with daytime irrigation and processing demand while a digester or gasifier is dispatchable to the evening peak and the thermal load (Diemuodeke *et al.*, 2024). Dispatchability has quantified value: removing bioenergy from a Ghanaian national pathway raises storage output by 37%, battery capacity by 29% and levelised cost by 27% (Mensah *et al.*, 2021).

This review treats the integrated holding as a single microgrid. Its objectives are to characterise the compound electrical and thermal load, review the conversion and power-conditioning subsystems, evaluate reported sizing and dispatch methods against standard reliability and cost metrics, and identify the empirical gaps obstructing design.

2. METHODOLOGY

2.1 Search Strategy and Study Selection

This is a narrative, conference-length review, illustrative of the current state of the art rather than exhaustive. Literature was identified by topic-based searching of Google Scholar, with full texts retrieved from the platforms it indexes, principally Elsevier, MDPI, Wiley, Frontiers, Springer Nature and Oxford University Press. Terms combined solar, photovoltaic, biomass, biogas, anaerobic digestion, gasification, agrivoltaic, hybrid renewable energy system, microgrid, livestock, poultry and cold storage with sub-Saharan Africa or individual country names; they were refined iteratively as the corpus developed, and the reference lists and related-article links of retained studies were followed. Records were eligible if published 2021-2026 in English in peer-reviewed journals or peer-reviewed conference proceedings, reporting original data, modelling or synthesis on: agrivoltaics and solar systems for irrigation, shading, grazing or farm electrification; digestion, co-digestion or gasification of manure or crop residue for farm energy; hybrid solar-biomass sizing, dispatch or techno-economic assessment in rural developing-country settings; post-harvest cold storage and precooling at farm scale; or microgrid coupling, power conditioning, energy management and metaheuristic sizing, subsystems sparsely treated in the agricultural literature. Utility-scale and urban work without an agricultural interface was excluded, as was any study stating no method or offering no extractable quantitative result. Studies outside the region were retained only for direct methodological relevance, such as the Fijian poultry-manure digestion trial, and are declared non-regional at each point of use. Claims resting on a single source triggered supplementary searching until corroborated or declared single-sourced where used. The search was conducted in Google Scholar and last updated on 1 September 2026, and resulted in 43 studies that met the inclusion criteria, of which 24 report sub-Saharan African sites or datasets.

2.2 Quality Appraisal and Character of the Evidence Base

Quality was appraised at point of use, and non-regional sources are declared at each use. The search was purposive rather than exhaustive and relied on openly retrievable English-language work, so the corpus is likely to under-represent unindexed, non-English or paywalled studies, a selection effect compounding the reporting bias considered in Section 3.7. Screening was carried out by a single reviewer, and stage-by-stage record counts were not retained. Two further features require statement: almost all system-level results are simulations, only Randle-Boggis *et al.* (2025) reporting operational agrivoltaic installations with measured multi-season output; and one reviewed study reports an itemised electrical and thermal breakdown (Baldi *et al.*, 2026), limiting how strongly the demand structure below can be asserted.

3. RESULTS AND DISCUSSION

3.1 Integrated Farm Load Characterisation

Livestock demands follow the animals' clock rather than the operator's: lighting, ventilation, feed preparation, water supply and, on dairy holdings, milking and chilling. Sub-metering of thirty German dairy farms shows these duties carry distinct load signatures (Vavouris *et al.*, 2025); no comparable African dataset was located, so structure is inferred from nameplate audits. Feed preparation is the largest discrete connected load on a poultry enterprise but not the largest consumer: a Nigerian layer audit at 25,000-bird scale reports a 16.5 kW hammer mill running briefly within

roughly 140 kWh/day dominated by pen-house lighting (Sasanya and Olaifa, 2022), while lighting on the Cameroonian broiler holding is minor at 2,418 kWh annually (Baldi *et al.*, 2026).

Irrigation is modelled rather than measured, and its character matters as much as its size: pumping is a deferrable motor load, flexible within the day because water can be stored, a mean smallholder system consuming about 255 kWh annually across roughly 75 operating days (Falchetta *et al.*, 2023).

Cold-chain demand is continuous and interruption-intolerant, so reliability rather than mean power drives design. Set points follow chilling-injury thresholds, 13 °C for banana and yam down to 7 °C for okra and pepper (Makule *et al.*, 2022), so a mixed tropical store runs near 13 °C rather than the sub-zero range of conventional cold storage. Solar cold stores run 5-10 kWp against 2-10 tons at COP 3.95, batteries taking 30-40% of cost (Amjad *et al.*, 2023). No reviewed source supplies a measured cooling profile for an African farm, the nearest entering refrigeration into the Mankramso model as a continuous 28.8 kWh/day load (Odoi-Yorke, Abaase, *et al.*, 2022): capacity can be inferred from tonnage, dispatch cannot, and dispatch determines storage.

Heat is a structural need: chicks held above ambient, wash water heated, harvests dried and produce cooled. On a three-house farm near Yaoundé producing roughly 72,000 birds annually, an 8 kW heater called below 27 °C consumes 57,744 kWh per year, about 94% of itemised farm energy (Baldi *et al.*, 2026); Emezirinwune *et al.* (2024) audit the same enterprise type but record electricity only, so the datasets cannot be compared. Non-regional broiler accounting agrees that brooding heat dominates total energy input, though ventilation dominates the electrical share as ambient temperature rises (Liang and Popp, 2025).

The cooling routes compare by coefficient of performance: a vapour-absorption cycle at COP 0.7 on 130 °C exhaust delivers 7.7 kW of cooling from 11 kW of heat (Diemuodeke *et al.*, 2024), a duty needing about 1.95 kW electrically at the vapour-compression COP of 3.95 (Amjad *et al.*, 2023), so absorption pays only where the heat would otherwise be rejected.

Aggregate figures allow sizing metrics to be derived. At Mankramso the load ranges 2.98-47.26 kW against 96 MWh annually, peaking 16:00-21:00 (Odoi-Yorke, Abaase, *et al.*, 2022). Taking the load factor as

$$LF = \frac{E_{ann}}{8760 \times P_{peak}} \quad (1)$$

gives a mean demand of 10.96 kW and a load factor near 0.23, which oversizes generation capacity, while the peak falling outside the generation window obliges energy to be time-shifted and so makes storage dominate lifetime cost. The audited Nigerian facility consumes 506,200 kWh annually, a mean of 57.8 kW, modelled as 527,250 kWh after a variability allowance (Emezirinwune *et al.*, 2024), against 3,544 kWh/yr at the Cameroonian farm, a caution against transferring published profiles. Table 1 assembles the load data reported.

Table 1: Reported and derived farm load metrics across the reviewed studies

Site	Reported	Derived
Yaoundé, Cameroon (Baldi <i>et al.</i> , 2026)	8 kW heater; 57,744 kWh/yr thermal; 3,544 kWh/yr electrical	Heating approximately 94% of itemised farm energy
Mankramso, Ghana (Odoi-Yorke, Abaase, <i>et al.</i> , 2022)	2.98-47.26 kW; 96 MWh/yr; peak 16:00-21:00	Mean 10.96 kW; load factor around 0.23
Abeokuta, Nigeria (Emezirinwune <i>et al.</i> , 2024)	Audited 1,386.85 kWh/day = 506,200 kWh/yr; modelled 1,444.52 kWh/day = 527,250 kWh/yr after a 5% variability setting, an increase of 4.2%; electrical only	Mean 57.8 kW audited (506,200 ÷ 8,760); 60.2 kW modelled; no thermal load recorded

3.2 Biomass Feedstock and Waste-to-Energy Conversion

Manure production per head differs by an order of magnitude between species (Kadam *et al.*, 2024), and threefold within one species by basis: poultry at 0.3 kg/head/day as excreted, 0.15 as collected litter and 0.09 as fresh manure (Baldi *et al.*, 2026; Naidu *et al.*, 2024). Poultry also gives the highest volumetric biogas yield among common manures, 231 Nm³ per tonne of dry manure against 60 for cattle manure (Augustyn *et al.*, 2021), and is the reference feedstock; its volatile fraction is reported between 0.61 and 0.85 on non-interchangeable bases (Ayantokun *et al.*, 2025), so the same yield spans 270-380 Nm³ per tonne of volatile solids. Blending streams of different character raises yield and stability (Kadam *et al.*, 2024), so the species mix is itself an asset. Supply is not constant: availability falls from 0.787 t/day in January to 0.315 t/day in July-October (Mwakitalima *et al.*, 2023), competing uses remove part of the residue stream (Adnane *et al.*, 2024), and about 6 of Ghana's 35 million tonnes of crop residue are unavailable for energy (Odoi-Yorke, Osei, *et al.*, 2022).

Biogas carries about 6 kWh/Nm³ at 55-65% methane (Naidu *et al.*, 2024). Stability is governed by the substrate carbon-to-nitrogen ratio, reported for poultry manure across a sevenfold range (Table 2) against a workable window given variously as 20-30, 16-25 or 20-35, optimal near 25, with ammonia inhibiting methanogenesis above 4 g/L (Adnane *et al.*, 2024; Ayantokun *et al.*, 2025); every entry in Table 2 except the Togolese and Nigerian measurements sits below it. The dispersion is not measurement error: nutrient content varies with region, diet and antibiotic use, bedding adds straw, feathers, lime or sawdust, and storage raises ammonia (Kadam *et al.*, 2024).

Table 2: Reported carbon-to-nitrogen ratios for poultry manure

Source	C/N	Material as described	Basis
Kadam <i>et al.</i> (2024)	Approx. 4.0	Chicken manure, elemental composition	Literature compilation; ultimate analysis depresses the ratio, the same source reporting 10.1
Baldi <i>et al.</i> (2026), Cameroon	6-12	Litter with bedding	Literature-derived
Naidu <i>et al.</i> (2024), Fiji	8	Manure with feathers, no sawdust	Calculator estimate
Brou <i>et al.</i> (2026), Togo	16.07	Manure with wood-chip bedding	Site measurement
Ayua <i>et al.</i> (2026), Nigeria	29.38	Dried droppings	Site measurement

Co-digestion brings the substrate into the window. Brou *et al.* (2026) report cumulative biogas rising from 210.73 to 348.65 mL/g VS at C/N 25 with cocoa pod husk, a 65.45% gain inside the 25-400% range reported generally (Adnane *et al.*, 2024). The second benefit is operational: in parallel reactors, a fall from 29 °C to 26 °C cut mono-digestion output by up to 80% while the co-digested reactor lost only 20% (Naidu *et al.*, 2024). The co-substrate is thus a stabiliser drawn from material already on a cropping holding, and mesophilic operation is the most widely adopted full-scale regime because it tolerates inhibitors and avoids thermophilic heating demand (Kadam *et al.*, 2024).

Uzoagba *et al.* (2024) assign low-moisture wastes to thermochemical and high-moisture waste to biochemical routes; Odoi-Yorke, Osei, *et al.* (2022) add scale, every gasification feedstock returning a negative net present value at 10 kW where every combustion feedstock was profitable, the two converging only at 100 kW because gasification carries the extra capital of gas cleaning and the gas engine. Integrated holdings sit at this scale, and fixed-bed downdraft reactors suit it best, yielding 0.1-1.2 g/Nm³ of tar against 20-100 from updraft units, but their window is narrow, 20-100 mm particles, ash near 0.5%, moisture below 20% (Ouedraogo, Sidibe, *et al.*, 2025), and most farm residues miss it: a West African trial on 25.2%-ash rice husk returned a cold gas efficiency of 36.6% against the 52.2-65% downdraft band (Ouedraogo, Richardson, *et al.*, 2025).

The electrical energy available from either route follows from

$$\begin{aligned}
 Q_{th} &= V_{gas} \times LHV_{gas}, \\
 P_e &= \eta_e \times Q_{th}, \\
 \eta_{cg} &= \frac{V_{gas} \times Y_{gas} \times LHV_{gas}}{LHV_{bio}}, \\
 \eta_{overall} &= \eta_{cg} \times \eta_e
 \end{aligned} \tag{2}$$

where Y_{gas} is specific gas production in Nm^3/kg (Ouedraogo, Richardson, *et al.*, 2025). Applying (2) shows why efficiency figures must be read on a common basis: a gasifier consuming 25-30 kg/h and producing 60-65 Nm^3/h at 4.5-5.0 MJ/ Nm^3 delivers roughly 82 kW of syngas thermal power against a genset rated 20 kWe and optimised to 24 kW, so the electrical efficiency near 24%, taken on the 20 kWe rating, is an engine figure, not a system one, and at the 16-20 MJ/kg typical of West African agro-residues cold gas efficiency is 54-68% and overall efficiency 13-16% (Diemuodeke *et al.*, 2024).

Yield figures can likewise mix bases. Augustyn *et al.* (2021) tabulate dry chicken manure at 381 kWh_e per tonne, implying 27% electrical efficiency, a full-scale cogeneration figure well above the 10-20% assumed for small farm gensets (Baldi *et al.*, 2026), so mixing the two over-predicts electrical output by roughly 1.4 to 2.8 times. At Tuna the same generator returns 140,661 kWh of recovered heat against 185,735 kWh of electricity (Diemuodeke *et al.*, 2024).

3.3 Microgrid Architecture, Power Electronics and Control

Among the off-grid reviewed systems only one describes a coupling arrangement, and then only as a nominal 12 V bus with no topology justification (Diemuodeke *et al.*, 2024), so guidance on the uncharacterised power-electronics layer comes from adjacent work. Jabari *et al.* (2025) describe the architecture as an AC subnet, a DC subnet and an interlinking converter, grid-forming units setting the voltage and frequency reference and grid-following units tracking it. An explicit two-bus arrangement is reported at Maizube farm, Sabon-daga, a 500 ha Nigerian holding carrying over 300 cattle alongside an orchard and drawing 980 kWh/day: Adetoro *et al.* (2023) place array, wind turbine and battery on a DC bus and the generators and heavy agricultural loads on an AC bus linked by a bidirectional converter, so rotary generators serve inductive machinery directly and inrush stress bypasses the power electronics. That system is grid-connected, an interconnection the islanded case does not carry, but the ordering of sources on the AC side is the one an off-grid farm faces.

For a farm microgrid whose largest loads are three-phase induction motors and whose biomass generator is an AC machine, AC coupling is the defensible default: the generator serves the motor loads directly, without a converter stage, at the cost of lower array-to-load efficiency. Classical droop assumes inductive line impedance, whereas in low-voltage networks resistance is comparable or larger, breaking active-reactive decoupling and causing inaccurate sharing and circulating currents (Jabari *et al.*, 2025), the case farm distribution presents and no reviewed study addresses. Inverter-connected photovoltaics contribute no rotational inertia, so sudden generation loss produces a faster rate of change of frequency unless grid-forming control emulates a synchronous response (Khan *et al.*, 2024); since thermal-first dispatch leaves the biomass generator off for most hours, a grid-forming battery inverter must hold the reference.

Converter ratings are reported in two of the reviewed systems on incompatible conventions: 81.4 kW against a 561 kW array, 6.9:1 against installed practice of 1.1-1.5:1 (Emezirinwune *et al.*, 2024), and 24.8 kW against a 20 kWp array at Tuna, 0.81:1 (Diemuodeke *et al.*, 2024). Neither states a rule, and no reviewed study reports inverter topology, harmonic distortion, regulation limits or protection coordination. Direct-on-line starting of mills and pelletisers imposes inrush currents of several times rated value, and a synchronous machine can supply roughly seven times rated current briefly where a grid-forming converter offers only about 20% overcurrent (Khan *et al.*, 2024). Machinery surveys reach the same requirement independently, reporting hammer mills at 2-15 kW and pelletisers from 3 kW upward and recommending variable-frequency drives for soft starting (Ogunobo and Onyenanu, 2025). A converter rated for motor starting rather than mean demand is therefore the implied requirement, which no reviewed sizing study addresses, and no measured power-quality data for an African farm microgrid was located.

Dispatch is either unspecified or set to the simulator's load-following rule (Emezirinwune *et al.*, 2024), whereas the evidence supports a thermal-first order of merit. Biogas converted to electricity at 10-20% engine efficiency discards most of its energy content against 90% in a gas heater (Baldi *et al.*, 2026); Naidu *et al.* (2024) reach the same ordering on emissions, 147.09 t CO₂ avoided annually by cooking-fuel displacement against 55.98 t via electricity; Rezaei *et al.* (2024) reach it on capital grounds, an organic Rankine cycle entering the optimum only if the electricity price roughly triples; and Augustyn *et al.* (2021) close it from the supply side, 95-99% of generated heat being absorbable by building heating and fermentation support.

A general constraint makes this ordering unusually favourable here. A biogas plant on average uses only half the heat it produces, and in Germany only 10% of producers use more than half (Augustyn *et al.*, 2021): cogeneration disappoints because the heat has no destination, and on a holding combining brooding, sanitation, drying and absorption cooling one exists. Capturing 130 °C engine exhaust serves the thermal load without touching the electrical bus (Diemuodeke *et al.*, 2024), so heat met this way never draws on the battery, the dominant cost term (Table 3). Load scheduling is then the highest-value control objective: forced-air precooling completes in 1-10 hours against 20-100 for room cooling (Makule *et al.*, 2022), and feed processing admits the same treatment (Sasanya and Olaifa, 2022). The one reviewed design that schedules milling does so as an assumed rather than optimised pattern (Odoi-Yorke, Abaase, *et al.*, 2022), and machinery-level guidance likewise places grinding and pelleting in the solar window (Ogunobo and Onyenanu, 2025).

Producer gas carries only 4.2-5.7 MJ/Nm³ and engines burning it have strict purity requirements. Tar is the dominant reliability constraint: below 450 °C it condenses and polymerises, corroding and clogging downstream components, and for unattended small units mechanical cleaning is favoured over catalytic or wet routes, which displace the problem into liquid-waste handling (Ouedraogo, Sidibe, *et al.*, 2025). A gasifier-genset should therefore run near its rated point with the battery absorbing the mismatch, a constraint no reviewed farm-scale study incorporates, though the Tuna simulation agrees, average electricity cost falling as the minimum load ratio rises (Diemuodeke *et al.*, 2024).

3.4 Sizing and Optimisation Methodology

All but two of the reviewed systems were sized in HOMER, the exceptions using particle swarm optimisation and mixed-integer linear programming (Table 3). A comparison of ten sizing tools against fourteen criteria (Silinto *et al.*, 2025) ranks HOMER the highest-scoring conventional model and confirms it admits thermal and deferrable loads, a capability no reviewed HOMER-based farm study exercised though the mixed-integer formulation schedules both (Baldi *et al.*, 2026); the same review records two structural limits, no multi-objective formulation and aggregation of all components into a single node with no internal power flow.

The wider literature applies metaheuristic search to the same problem. One reviewed study coupled HOMER with a grey wolf optimiser, reducing levelised cost from USD0.1109/kWh to USD0.0887/kWh (Mwakitalima *et al.*, 2023), a margin reflecting a different search space, since HOMER enumerates near-exhaustively over its own. In multi-objective formulations cost, reliability and emissions genuinely conflict: on a grid-connected solar-biogas system with storage, a non-dominated sorting whale optimisation algorithm balanced net present cost against emissions with better convergence than grey wolf and particle swarm benchmarks (Agajie *et al.*, 2023). Every reviewed farm study nonetheless minimises a single cost objective, which conceals the trade-off rather than resolving it.

Reliability is expressed as loss of power supply probability,

$$LPSP = \frac{\sum E_{unmet}}{\sum E_{demand}} \quad (3)$$

and cost as the levelised cost of energy,

$$LCOE = \frac{C_{cap} \times CRF + C_{O\&M} + C_{rep} + C_{fuel}}{E_{served}} \quad (4)$$

where $CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1}$ at real discount rate i , replacements are present-worthed,

salvage credited, and E_{served} is electricity delivered; crediting heat gives a cost of energy, not of electricity (Diemuodeke *et al.*, 2024). The reliability metric is not reported under a single name across the corpus, appearing as loss of energy probability in Emezirinwune *et al.* (2024) and as loss of energy probability of power in (Mwakitalima *et al.*, 2023); the quantity is identical and the studies are compared on that basis.

Applied to Abeokuta, the fully renewable configuration leaves 399 kWh/yr unserved against a 527,250 kWh modelled load, a ratio of 0.000757, at USD0.261/kWh against USD0.206/kWh for the diesel-containing optimum, a premium of 26.7% (Emezirinwune *et al.*, 2024): the premium buys the last fraction of a point of availability, a design choice rather than a technical limit. Each metric is reported in only two of the reviewed systems.

3.5 Techno-Economic, Environmental and Cogeneration Synthesis

Table 3 assembles the reviewed sub-Saharan solar-biomass systems; only one is sited on a holding combining livestock with a cropped area, and there the crop enterprise carries no modelled electrical load. The hybrids sit below diesel and above grid supply: Mankramso delivers USD0.265/kWh against USD0.980/kWh for diesel alone, 64% above Ghana's average tariff (Odoi-Yorke, Abaase, *et al.*, 2022). Where no grid exists the comparison inverts, break-even grid extension at Simboya being 0.19 km against a nearest connection 79.7 km away (Mwakitalima *et al.*, 2023).

Table 3: *Reported solar-biomass hybrid systems for sub-Saharan Africa*

Site	Scope	Configuration	Method	LCOE	Discount rate / life	Storage share
Mankramso, Ghana	Rural community	PV 50 kW; biogas 20 kW; battery 237 kWh	HOMER	\$0.265/kWh	12% / 25 yr (batteries 5 yr)	45.6% of NPC
Simboya, Tanzania	Rural village	PV 40 kW; biogas 25 kW; battery 144 kWh	HOMER, then grey wolf	\$0.1109/kWh (HOMER); \$0.0887/kWh (grey wolf)	8% nominal, 4% inflation / 25 yr (batteries 10 yr)	45.9% of capital
Tuna, Ghana	School (CHP)	PV 20 kWp; gasifier-genset 24 kW; battery 78 kWh	HOMER Pro	€0.295/kWh	7.5% / 25 yr	Not reported
Abeokuta, Nigeria	Poultry facility	PV 561 kW; gasifier 10 kW; diesel 88 kW; converter 81.4 kW (the fully renewable case substitutes a 50-kW biomass generator)	HOMER	\$0.206/kWh diesel-containing optimum; \$0.261/kWh fully renewable	11.5% / 25 yr	Approx. 51% of NPC
Sabon-daga, Nigeria	Dairy farm with orchard; grid-connected, 20% availability	PV 248 kW; wind 2 kW; biogas 22 kW; diesel 92 kW; battery 658 kWh	PSO	\$0.148/kWh	15% / 25 yr	Not reported
Yaoundé, Cameroon	Poultry farm	PV 70 kW; digester to 23.2 kW	MILP	€2,680-6,980/yr (annual cost)	Not reported / 20 yr (10 yr batteries)	Battery at farm only in unconstrained case

Note. Yaoundé reports a total annualised system cost, not a levelised cost, and is not comparable with the other rows. Costs are in the currency and year of the source study, without exchange-rate normalisation. The Sabon-daga levelised cost includes grid import at USD0.07/kWh and is not comparable with the off-grid rows.

The biomass share of generation spans more than an order of magnitude across the three hybrids reporting it, 49% at Mankramso, 9.6% at Simboya and 2.77% at Abeokuta, and the cause is allocation, not resource. At Simboya the biogas unit generates 7,707 kWh against 72,500 kWh from the array on 23.1 t of feedstock annually, about 63 kg/day against a collected availability of 0.315-0.787 t/day, a capacity factor of 3.52%: the constraint is how much manure is committed to the generator, the balance going to household cooking gas (Mwakitalima *et al.*, 2023). At Mankramso a 20 kW unit against a 50 kW array carries 49% because it runs when the array cannot (Odoi-Yorke, Abaase, *et al.*, 2022), a split independently tabulated by Overen *et al.* (2024). Any quoted biomass fraction therefore describes dispatch and allocation, not the farm's resource.

Storage dominates lifetime cost, the most consistently reproduced result: all three hybrids reporting a share place batteries at or above 45% of net present or capital cost, denominators that are not interchangeable, with a further 30-40% share in solar cold storage (Amjad *et al.*, 2023). Quadrupling feedstock price from USD2 to USD8 per tonne raises levelised cost by only 5% where manure is collected on site (Odoi-Yorke, Abaase, *et al.*, 2022), whereas cost is materially sensitive for purchased groundnut shells (Diemuodeke *et al.*, 2024), an argument for on-farm supply.

Diesel displacement is the principal environmental benefit reported: at Abeokuta annual emissions fall from 399,855 kg of CO₂ under the diesel-dominant alternative to 31,840 kg at the optimum and 15.8 kg diesel-free (Emezirinwune *et al.*, 2024), and at Simboya from 635,966 kg under diesel-only supply to 0.531 kg fully renewable (Mwakitalima *et al.*, 2023). These are combustion figures at about 2.66 kg CO₂/L, with biogenic carbon zero-rated and methane slip and digestate storage outside the boundary, so the residual kilogrammes measure diesel displaced rather than the farm's footprint. Open storage of manure loses up to 70% of its nitrogen within 24 hours in humid tropical conditions (Kadam *et al.*, 2024), so digestion conserves more than energy alone.

Thermal recovery is rarely evaluated: only the Tuna configuration, delivering 110.9 MWh of heat and 7.7 kW of cooling (Diemuodeke *et al.*, 2024), and the Yaoundé optimisation, where biogas serves brooding heat (Baldi *et al.*, 2026). Sizing either requires a correction the reviewed designs omit: Rezaei *et al.* (2024) report a fermenter consuming on average 45% of the heat produced, rising to about 60% in the cold season, so the heat available to the farm is

$$Q_{avail} = Q_{gross} (1 - f_{par}) \text{ is approximately } 0.45-0.60 \quad (5)$$

The figure is a temperate input coefficient rather than a measurement, but the correction cannot be omitted: a digester sized by matching nominal production to brooding demand will under-deliver by roughly half. The tropical case is likely more favourable, ambient temperatures sitting closer to the mesophilic set point (Adnane *et al.*, 2024), and solar water heating raised a Nigerian pilot digester's average temperature 35% on sunny relative to rainy days (Ayua *et al.*, 2026), placing part of the parasitic demand on the solar side.

Digestate is usually presented as an environmental co-benefit and is closer to an economic foundation. Zielińska and Bułkowska (2024) state the constraint: nitrogen and phosphorus in the liquid fraction are simultaneously too concentrated for discharge standards and too dilute to serve as fertiliser, and the mature recovery routes stay viable only above roughly 50 mg P/L or 1,000-1,500 mg/L ammonia, below which, the smallholder case, the nutrients are effectively unrecoverable. Naidu *et al.* (2024) show the value where a market exists, payback falling from 16.8 years to under three once 5% of digestate is sold; where none exists, the correct valuation is the fertiliser purchase avoided on site. These are transaction constraints, which makes co-location decisive: applied where produced, digestate is neither upgraded, transported nor priced, and proximity of livestock and co-substrate to the digester is independently identified as a commercialisation requirement (Kadam *et al.*, 2024).

3.6 Field-Level Implementation Challenges

Four technical constraints recur. Feedstock volatility is seasonal (Mwakitalima *et al.*, 2023), so sizing against the minimum month is the defensible heuristic. Gasifier tar fouling limits engine life, and nearly all gasification plants deployed for heat and power in this region have failed (Ouedraogo, Sidibe, *et al.*, 2025). Photovoltaic soiling is more severe than global defaults allow, modelled West African losses exceeding 50% during the Harmattan (Isaacs *et al.*, 2023), and no reviewed farm study applies a region-specific derating, so reported yields are optimistic. Finally, storage is 51% of net present cost on a four-year battery life, replacement across all components 34% against 11% for fuel (Emezirinwune *et al.*, 2024).

Capital cost and credit access dominate the economic constraints, ranking above technical ones across the solar-cooling studies screened by Amjad *et al.* (2023). Pay-as-you-go and lease-to-own arrangements still require 20-25% upfront, and on one estimate only about 6% of the region's farmers could afford solar irrigation individually (Durga *et al.*, 2024); Tanzanian smallholders meet input costs only after sale, so cannot prepay for storage services (Rutta, 2022). Even a 100% capital subsidy leaves levelised cost 32% above Ghana's lifeline tariff, because capital is barely two-fifths of lifetime cost (Odoi-Yorke, Abaase, *et al.*, 2022), a result reproduced by Odoi-Yorke, Osei, *et al.* (2022) and by a South African design that turns loss-making without a 60% subsidy (Overen *et al.*, 2024), while in the

Yaoundé optimisation the digester enters only under a litter-disposal constraint or with external financing (Baldi *et al.*, 2026).

Targets exist without accountability: Nigeria set 90% electricity access by 2030 with no public progress reports (Uzoagba *et al.*, 2024), and Nyarko *et al.* (2023) find monitoring largely absent, a six-country inspection identifying projects with neither maintenance plans nor monitoring systems. A multi-regional review records the same pattern of weak policy frameworks and limited stakeholder coordination across Nigeria, Kenya and South Africa (Obuseh *et al.*, 2025).

3.7 Convergence, Divergence and Empirical Gaps

Table 4 separates claims supported by multiple independent sources from those resting on one study or stated on differing bases.

Table 4: *Points of convergence across the reviewed literature*

Claim	Status	Basis
Storage dominates lifetime cost	Convergent	All three hybrids reporting a share are at 45% or above of NPC or capital, denominators not interchangeable; 30-40% for solar cold storage
Thermal use before electrical conversion	Convergent	Engine efficiency, emissions, capital cost and heat-utilisation ceiling agree; emissions line contingent on displaced fuel
Co-digestion corrects C/N and raises yield	Convergent	Batch assay and reviews agree on yield; one pilot corroborates stability
Capital subsidy alone is insufficient	Convergent	Two studies sharing a lead author, plus independent cost-type and South African corroboration
Shiftable processing belongs in the generation window	Partially corroborated	One assumed schedule in a community model plus independent machinery-level design guidance; no optimised or measured demonstration
Thermal demand dominates poultry load	Partially corroborated	One itemised regional audit; direction supported by non-regional broiler accounting; a second regional audit records no thermal load
Digester parasitic heat at 45-60%	Single-sourced, non-regional	A single Swiss study, where the value is an input coefficient attributed to secondary CHP guidance rather than a measurement; alters sizing materially
Biogas yield per tonne vs. engine efficiency	Stated on different bases	Plant-level 1.65 kWhe/Nm ³ vs 10-20% genset efficiency; 231 Nm ³ /t dry manure = 0.27-0.38 m ³ /kg VS across the reported volatile-solids range
Gasifier electrical efficiency	Single plant, two bases reconciled	24% engine and 13-16% overall are one plant on two bases
Bus architecture and power quality	Addressed once, outside the off-grid set	One grid-connected Nigerian farm study specifies a two-bus topology; no off-grid system justifies a coupling arrangement, states a converter sizing rule, or reports power-quality data

Five empirical gaps follow. First, the holding is not modelled as one system: the audited poultry facility reports no thermal demand (Emezirinwune *et al.*, 2024), agricultural load is entered as zero at village scale (Mwakitalima *et al.*, 2023), both village-scale solar-biogas designs size digesters from livestock censuses treating manure purely as fuel, and at Maizube farm the itemised load covers animal housing and milk handling only, with no irrigation or post-harvest demand in the optimisation (Adetoro *et al.*, 2023). That integrated configuration has not been examined. Second, demand is not disaggregated: with one itemised electrical and thermal breakdown available (Baldi *et al.*, 2026), the thermal-first order of merit rests on multiply-sourced efficiency arguments matched against a singly-

sourced demand structure. Third, cooling has capacity but no demand shape, leaving a schedulable load unschedulable. Fourth, the power-electronics layer is unspecified for the off-grid farm case (Table 4). Fifth, continuous farm-scale digestion is untested regionally, the reviewed pilots operating at 10 L in Nigeria (Ayua *et al.*, 2026) and 500 L in Fiji (Naidu *et al.*, 2024), and no African livestock agrivoltaic instance was located, the field studies identified being United States sheep systems (Bacon *et al.*, 2025) and the one financial analysis likewise North American (Gasch *et al.*, 2025).

A limitation of the evidence base qualifies these gaps and the convergence in Table 4. Every hybrid reviewed reports a cost advantage over diesel, and no reviewed study reports an uncompetitive configuration at farm scale. Simulation studies returning unfavourable outcomes are less likely to be submitted and published than favourable ones, so the absence of negative results is consistent with reporting practice as well as with system performance. Table 4 therefore indicates that these configurations perform under the modelling assumptions their authors adopted, not that a representative sample of sites would return equivalent results.

3.8 Recommendations for Future Sizing Models and Field Implementation

Four recommendations follow. First, instrument a working integrated holding for electrical and thermal demand at end-use resolution over a full agricultural cycle. Second, formulate sizing as a multi-objective problem over levelised cost, loss of power supply probability and renewable fraction, with the digester's unit-commitment decision represented explicitly and the fermenter parasitic fraction of (5) applied to gross thermal output; since that fraction rests on a single non-regional coefficient, establishing the regional value is part of the work. Third, specify the power-electronics interface against motor-starting duty rather than mean demand, and apply a region-specific soiling derating from local particulate data. Fourth, treat local characterisation as preceding sizing: panel densities associated with yield loss in temperate meta-analysis improved several crop yields at two East African sites (Randle-Boggis *et al.*, 2025), that expectation itself resting on coverage thresholds across fifty installations (Widmer *et al.*, 2024).

4. CONCLUSION

Integrated livestock-horticulture holdings resolve internally three constraints that limit on-farm digestion elsewhere: the substrate carbon-to-nitrogen imbalance, corrected by a co-substrate the cropping enterprise already produces; the thermal instability that co-substrate buffers; and the transaction cost of digestate, which disappears when the material is applied where it is produced. Co-location is therefore an economic precondition of the design, and the same reasoning governs heat.

Three design principles follow. Gas should be allocated to heat before conversion, and the digester sized against thermal demand referred to gross rather than net output, because the fermenter consumes a substantial share of the heat produced; the only quantification available, 45-60%, is a single non-regional input coefficient (Rezaei *et al.*, 2024), so the design carries forward its approximate magnitude, not its precise value. Storage is the dominant cost term, so scheduling shiftable load into the generation window is the control objective with the largest economic return. Published parameters are artefacts of the method and site that produced them, so local characterisation precedes sizing rather than refines it. The principal limitation is the evidence base itself: every system-level result reported for a solar-biomass hybrid is a simulation, digestion results are at bench and pilot scale, the cooling load is uncharacterised in time, the power-electronics layer is unspecified, the corpus contains no negative techno-economic result, and the demand structure has been itemised on a single farm. The configuration is well founded in its parts and unproven as a whole; an instrumented pilot is the next contribution needed.

5. REFERENCES

Adetoro, S. A., Olatomiwa, L., Tsado, J., & Dauda, S. M. (2023). An enhanced combined dispatch strategy for a grid-connected hybrid renewable energy system. *Green Energy and Resources*, 1(4), 100044. <https://doi.org/10.1016/j.gerr.2023.100044>

- Adnane, I., Taoumi, H., Elouahabi, K., Lahrech, K., & Oulmekki, A. (2024). Valorization of crop residues and animal wastes: Anaerobic co-digestion technology. *Heliyon*, 10(5). <https://doi.org/10.1016/j.heliyon.2024.e26440>
- Agajie, T. F., Fopah-Lele, A., Amoussou, I., Ali, A., Khan, B., & Tanyi, E. (2023). Optimal Design and Mathematical Modeling of Hybrid Solar PV–Biogas Generator with Energy Storage Power Generation System in Multi-Objective Function Cases. *Sustainability*, 15(10), 1-26. <https://doi.org/10.3390/su15108264>
- Amjad, W., Munir, A., Akram, F., Parmar, A., Precoppe, M., Asghar, F., & Mahmood, F. (2023). Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review. *Clean Energy*, 7(3), 635-653. <https://doi.org/10.1093/ce/zkad015>
- Augustyn, G., Mikulik, J., Rumin, R., & Szyba, M. (2021). Energy self-sufficient livestock farm as the example of agricultural hybrid off-grid system. *Energies*, 14(21), 7041. <https://doi.org/10.3390/en14217041>
- Ayantokun, A. S., Matambo, T. S., Rashama, C., Van der Merwe, I., & Van Niekerk, J. A. (2025). A critical review of food waste and poultry manure anaerobic co-digestion: An eco-friendly valorization for sustainable waste management and biogas production. *Frontiers in Sustainable Food Systems*, 9, 1695945. <https://doi.org/10.3389/fsufs.2025.1695945>
- Ayua, T. J., Ambrose, I. S., & Omaku, D. S. (2026). Anaerobic digestion of poultry droppings for biogas production: a pilot study of renewable energy technology in the agricultural sector. *BMC Environmental Science*, 3(1), 7. <https://doi.org/10.1186/s44329-026-00048-8>
- Bacon, T., Monlezun, A., Hong, M., Macknick, J., De Vries, N., Edwards-Callaway, L., & Paustian, K. (2025). Agrivoltaic grazing systems for a sustainable future: A multi-disciplinary review & gap analysis. *Earth's Future*, 13(8), e2024EF005429. <https://doi.org/10.1029/2024EF005429>
- Baldi, F., Santucci, M., Bini, M. E., Kenne, Y., Beozzo, S., & Bonoli, A. (2026). Valorization of poultry litter through anaerobic digestion in small-scale farm energy systems: A techno-economic case study in Cameroon. *Energies*, 19(9), 2024. <https://doi.org/10.3390/en19092024>
- Brou, A. P. E., Gbiete, D., Nougbléga, Y., & Narra, S. (2026). Optimizing biogas production from poultry manure and cocoa pod husks co-digestion: implications for circular bioeconomy and decentralized energy systems in West Africa. *Frontiers in Bioengineering and Biotechnology*, 14, 1845247. <https://doi.org/10.3389/fbioe.2026.1845247>
- Chanda, H., Mohareb, E., Peters, M., Harty, C., Green, M., Kasanda, E. B., & Shibata, N. (2026). Energy transitions in Sub-Saharan Africa: Policy recommendations for charcoal trade, solar PV adoption, and sustainability in rural Zambia. *Energy Policy*, 208, 114936. <https://doi.org/10.1016/j.enpol.2025.114936>
- Diemuodeke, O. E., Vera, D., Ojapah, M. M., Nwachukwu, C. O., Nwosu, H. U., Aikhuele, D. O., . . . Seidu Nuhu, B. (2024). Hybrid Solar PV–Agro-Waste-Driven Combined Heat and Power Energy System as Feasible Energy Source for Schools in Sub-Saharan Africa. *Biomass*, 4(4), 1200-1218. <https://doi.org/10.3390/biomass4040067>
- Durga, N., Schmitter, P., Ringler, C., Mishra, S., Magombeyi, M. S., Ofosu, A., . . . Verma, S. (2024). Barriers to the uptake of solar-powered irrigation by smallholder farmers in sub-saharan Africa: A review. *Energy strategy reviews*, 51, 101294. <https://doi.org/10.1016/j.esr.2023.101294>
- Emezirinwune, M. U., Adejumbi, I. A., Adebisi, O. I., & Akinboro, F. G. (2024). Off-grid PV/biomass/DG/battery hybrid renewable energy as a source of electricity for a farm facility. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, 10, 100808. <https://doi.org/10.1016/j.prime.2024.100808>
- Falchetta, G., Semeria, F., Tuninetti, M., Giordano, V., Pachauri, S., & Byers, E. (2023). Solar irrigation in sub-Saharan Africa: Economic feasibility and development potential. *Environmental Research Letters*, 18(9), 094044. <https://doi.org/10.1088/1748-9326/acefe5>

- Gasch, A., Lara, R., & Pearce, J. M. (2025). Financial analysis of agrivoltaic sheep: Breeding and auction lamb business models. *Applied Energy*, 381, 125057. <https://doi.org/10.1016/j.apenergy.2024.125057>
- Isaacs, S., Kalashnikova, O., Garay, M. J., van Donkelaar, A., Hammer, M. S., Lee, H., & Wood, D. (2023). Dust soiling effects on decentralized solar in West Africa. *Applied Energy*, 340, 120993. <https://doi.org/10.1016/j.apenergy.2023.120993>
- Jabari, M., Ghoreishi, M., Bragatto, T., Santori, F., Cresta, M., Geri, A., & Maccioni, M. (2025). Advancing hybrid ac/dc microgrid converters: Modeling, control strategies, and fault behavior analysis. *Energies*, 18(23), 6302. <https://doi.org/10.3390/en18236302>
- Kadam, R., Jo, S., Lee, J., Khanthong, K., Jang, H., & Park, J. (2024). A review on the anaerobic co-digestion of livestock manures in the context of sustainable waste management. *Energies*, 17(3), 546. <https://doi.org/10.3390/en17030546>
- Khan, M., Wu, W., & Li, L. (2024). Grid-forming control for inverter-based resources in power systems: A review on its operation, system stability, and prospective. *IET Renewable Power Generation*, 18(6), 887-907. <https://doi.org/10.1049/rpg2.12991>
- Liang, Y., & Popp, M. (2025). Economic Impact of Energy Accounting Schemes for Commercial Systems on a Broiler Farm with Power Demand and Generation. *Energies*, 18(4). <https://doi.org/10.3390/en18040979>
- Makule, E., Dimoso, N., & Tassou, S. A. (2022). Precooling and cold storage methods for fruits and vegetables in Sub-Saharan Africa—A review. *Horticulturae*, 8(9), 776. <https://doi.org/10.3390/horticulturae8090776>
- Mensah, T. N. O., Oyewo, A. S., & Breyer, C. (2021). The role of biomass in sub-Saharan Africa's fully renewable power sector—the case of Ghana. *Renewable Energy*, 173, 297-317. <https://doi.org/10.1016/j.renene.2021.03.098>
- Mwakitalima, I. J., Rizwan, M., & Kumar, N. (2023). Integrating solar photovoltaic power source and biogas energy-based system for increasing access to electricity in rural areas of Tanzania. *International Journal of Photoenergy*, 2023(1), 7950699. <https://doi.org/10.1155/2023/7950699>
- Naidu, G. M., Raturi, A., & Mani, F. S. (2024). Anaerobic digestion of poultry manure to power a poultry farm in Ba: Pilot and techno-economic study. *Heliyon*, 10(17). <https://doi.org/10.1016/j.heliyon.2024.e36325>
- Nyarko, K., Whale, J., & Urme, T. (2023). Drivers and challenges of off-grid renewable energy-based projects in West Africa: A review. *Heliyon*, 9(6). <https://doi.org/10.1016/j.heliyon.2023.e16710>
- Obuseh, E., Eyenubo, J., Alele, J., Okpare, A., & Oghogho, I. (2025). A systematic review of barriers to renewable energy integration and adoption. *Journal of Asian Energy Studies*, 9, 26-45. <https://doi.org/10.24112/jaes.090002>
- Odoi-Yorke, F., Abaase, S., Zebilila, M., & Atepor, L. (2022). Feasibility analysis of solar PV/biogas hybrid energy system for rural electrification in Ghana. *Cogent Engineering*, 9(1), 2034376. <https://doi.org/10.1080/23311916.2022.2034376>
- Odoi-Yorke, F., Osei, L. K., Gyamfi, E., & Adaramola, M. S. (2022). Assessment of crop residues for off-grid rural electrification options in Ghana. *Scientific African*, 18, e01435. <https://doi.org/10.1016/j.sciaf.2022.e01435>
- Ogunobo, R., & Onyenanu, I. U. (2025). Integration of renewable energy systems in poultry feed production machines: A pathway to sustainable agro-mechanization. *BW Academic Journal*, 2. <https://bwjournal.org/index.php/bsjournal/article/view/3425>
- Ouedraogo, H., Richardson, Y., & Zoungrana, L. (2025). Optimizing gasification in downdraft fixed-bed gasifier through experimental and kinetic modeling. *Case Studies in Thermal Engineering*, 68, 105910. <https://doi.org/10.1016/j.csite.2025.105910>
- Ouedraogo, H., Sidibe, S. D. S., & Richardson, Y. (2025). Advancing small-scale biomass gasification (10–200 kW) for energy access: Syngas purification, system modeling and the role of artificial

- pintelligence-A review.
- Energy Conversion and Management*
- : X, 27, 101059.
- <https://doi.org/10.1016/j.ecmx.2025.101059>
- Overen, O. K., Obileke, K., Meyer, E. L., Makaka, G., & Apeh, O. O. (2024). A hybrid solar–biogas system for post-COVID-19 rural energy access. *Clean Energy*, 8(1), 84-99. <https://doi.org/10.1093/ce/zkad070>
- Randle-Boggis, R., Barron-Gafford, G., Kimaro, A., Lamanna, C., Macharia, C., Maro, J., . . . Hartley, S. (2025). Harvesting the sun twice: energy, food and water benefits from agrivoltaics in East Africa. *Renewable and Sustainable Energy Reviews*, 208, 115066. <https://doi.org/10.1016/j.rser.2024.115066>
- Rezaei, F., Burg, V., Pfister, S., Hellweg, S., & Roshandel, R. (2024). Spatial optimization of industrial symbiosis for heat supply of agricultural greenhouses. *Journal of Industrial Ecology*, 28(6), 1507-1523. <https://doi.org/10.1111/jiec.13543>
- Rutta, E. W. (2022). Understanding barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction: Insights from small-scale farmers in Tanzania. *Frontiers in Sustainable Food Systems*, 6, 990528. <https://doi.org/10.3389/fsufs.2022.990528>
- Sasanya, B. F., & Olaifa, O. (2022). Analysis of energy consumption in poultry management for table egg production in Nigeria. *Heliyon*, 8(8), e10053. <https://doi.org/10.1016/j.heliyon.2022.e10053>
- Silinto, B. F., Van der Laag Yamu, C., Zuidema, C., & Faaij, A. P. (2025). Hybrid renewable energy systems for rural electrification in developing countries: A review on energy system models and spatial explicit modelling tools. *Renewable and Sustainable Energy Reviews*, 207, 114916. <https://doi.org/10.1016/j.rser.2024.114916>
- Uzoagba, C., Onwualu, P. A., Okoroigwe, E., Kadivar, M., Oribu, W. S., Mguni, N. G., . . . Aperebo, M. (2024). A review of biomass valorization for bioenergy and rural electricity generation in Nigeria. *Cureus J. Eng*, 1-16. <https://doi.org/10.7759/s44388-024-00065-w>
- Vavouris, A., Stankovic, L., Stankovic, V., & Shi, J. (2025). FIELD: a comprehensive FarmIng Electrical Load measurements dataset from 30 three-phase dairy farms in Germany. *Scientific Data*, 12(1), 1830. <https://doi.org/10.1038/s41597-025-06094-2>
- Widmer, J., Christ, B., Grenz, J., & Norgrove, L. (2024). Agrivoltaics, a promising new tool for electricity and food production: A systematic review. *Renewable and Sustainable Energy Reviews*, 192, 114277. <https://doi.org/10.1016/j.rser.2023.114277>
- Zebra, E. I. C., van der Windt, H. J., Nhumaio, G., & Faaij, A. P. (2021). A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*, 144, 111036. <https://doi.org/10.1016/j.rser.2021.111036>
- Zielińska, M., & Bułkowska, K. (2024). Sustainable management and advanced nutrient recovery from biogas energy sector effluents. *Energies*, 17(15), 3705. <https://doi.org/10.3390/en17153705>