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Is Bigger Better? Exploring Sustainable Delivery Models for Multi-Scale East African Smart Biogas Systems

Benjamin L. Robinson [1,*], Winfred Pemba [2], Viola Ninsiima [3], Gideon Muhindo [3], Admore Chiumia [2], Mike J. Clifford [1], Joseph Hewitt [4] and Michel Muvule [3]

[1] Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[2] Green Impact Technologies, Area 47, Lilongwe 30487, Malawi
[3] Biogas Solutions Uganda Limited, Plot 36 Luthuli Rise, Bugolobi, Kampala P.O. Box 8339, Uganda
[4] School of Energy, Construction and Environment, Coventry University, Coventry CV1 5FB, UK
* Correspondence: ben.robinson2@nottingham.ac.uk

Abstract: With the deadline for the 17 United Nations Sustainable Development Goals (SDGs) on the horizon, the global community is forging a pathway through the ever-more complex global ecosystem to 2030. Whilst household-scale AD systems have seen significant attention, the community and commercial scales remain significantly under-researched. This paper aims to explore the state-of-the-art in energy access, AD and smart metering, and presents three scales of AD system delivery models which can potentially unlock meaningful pathways to energy access and the completion of SDG7. We achieve this through a two-phase qualitative methodology: first, an in-person participatory market systems development workshop in Malawi, and second, by leveraging experts' knowledge of the Uganda and Malawian biogas sector to develop the case studies that illustrate the three scales of the AD system delivery model. Our findings analyse these delivery models, exploring the disconnection between digester size and delivery model, overcoming delivery model weaknesses through blended approaches to energy access, the role of digitalisation, and the importance of tailoring the delivery models to specific contexts. Ultimately, by drawing on real-world examples of AD system delivery models, this paper concludes by proposing a novel entire ecosystems or systems approach to biogas implementation through the blending of different scales of implementation.

Keywords: biogas; delivery models; Uganda; Malawi; clean cooking; SDG7

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1. Introduction

With the deadline for the 17 United Nations Sustainable Development Goals (SDGs) [1] on the horizon, the global community is keeping up the pressure to find a pathway through the ever-more complex global ecosystem to 2030. Within SDG7—sustainable energy for all—these innovative pathways led, in recent years, to the creation of market-based models for the deployment of modern, reliable, and sustainable energy systems and services in collaboration with some of the most at-risk and hard-to-reach communities [2]. Delivery or implementation models within the energy sector are defined as "the combination of the technology, finance, management activities, policy support, legal arrangements and relationship types required to supply energy to a group of people or end-users" [3]. This means that they often focus on connecting a specific technology with a specific socio-cultural, environmental, and financial implementation context. For example, Bisaga and To [4] connect modern energy cooking services at the individual and household levels with a selection of financial models which are relevant to various country-specific humanitarian contexts. Market-based models in the energy sector include both external interventions (end-user subsidies, product/tariff subsidy, results-based financing, etc.) and business models (customer finance, PAYGo (mobile-enabled), flexible repayments, barter payments, cross-subsidies, and community-saving schemes, etc.) that aim to "have an impact on the affordability of energy products and services" [5], usually across a diverse range of partners. This results in a complex weave of private sector, international development, and often academic stakeholders which brings unique challenges, yet seems to provide a model of energy system and service deployment that can match the scale of the global challenge for universal energy access. This new generation of systems and services underlines the interconnected and cross-cutting nature of energy access by encompassing delivery or implementation models across the cooking, cooling, lighting, heating, and transport sectors, touching on energy production, distribution, and consumption as well as having a multi-scale focus—especially across households, communities, and commercial stakeholders.

Given the multifaceted nature of energy access, it is difficult to accurately identify the scale of the energy access challenge, especially as definitions of meaningful energy access differ between governments, donors, implementing partners, and evaluators [6]. As of 2022, roughly 600 million people do not have access to electricity in sub-Saharan Africa (four in five people) and many more have inconsistent or irregular access, 2.3 billion globally do not have access to clean cooking technologies [2], and many of these stack multiple clean and "unclean" technologies to satisfy their complex and diverse energy needs [7–9]. The global context shapes the technological, sociological, and behavioural nature of the clean cooking sector, where leveraging the products of anaerobic digestion (AD) through various designs of biodigesters provides one option for access to clean cooking. Typically, AD systems (or biodigesters) are sealed units in which biological waste (such as dung, food waste, and agricultural waste) is digested in a limited oxygen environment to produce biogas, primarily used for cooking, and digestate, a type of high-nutrient liquid fertiliser [10–12] used directly as liquid fertiliser or further processed into foliar feed or compost. This means that the use of AD at the household, community, and commercial level results in multiple direct impacts, including waste management, clean cooking gas, transitions from synthetic to organic fertilisers, and cost savings for users (as the gas and digestate are produced from waste streams). Additionally, unlike other biofuels, the production of biogas does not compete with food crops for land, fertilisers, and water. Indirectly, AD has wider impacts on water quality, deforestation, climate change mitigation through carbon offsets, and local employment (through technicians supporting operation and maintenance). However, the implementation, operation, and maintenance of AD systems still see several well-documented challenges. For example, Singh et al. [13] outline technical and operational challenges when setting up decentralised AD plants of any scale, including feedstock sourcing, optimal site selection, intricate planning and designing, robust infrastructure development, sophisticated monitoring and control systems, efficient waste biomass and slurry management, and the imperative factor of public acceptance and awareness, whilst Hewitt et al. [14] outline several factors determining failure and abandonment including poor construction and installation, sub-optimal feeding practices, operation and maintenance issues, and training provision and knowledge erosion.

Many clean cooking initiatives fail due to the misalignment of project assumptions and end-user expectations [15]; this gap is often found within the complex socio-cultural, environmental, and financial context in which clean cooking initiatives are implemented. Biogas projects are no different, the context often dictates the viability, sustainability, and longevity of biogas systems and services. In this section, we provide a detailed overview of the country contexts considered in this paper: Uganda and Malawi.

Despite Uganda's rich energy resources (hydropower, biomass, solar energy, geothermal, peat, and wind), 89.4% of the total energy supply (and consumption) is through biofuels and waste [16], and only 1% have access to clean cooking technologies and services [2]. The household-scale biogas sector is one pathway to clean cooking for all and has seen slow growth over the last 70 years. AD technology was first introduced in Uganda in the 1950s, and since then, a multitude of initiatives have been undertaken by private entrepreneurs, NGOs, government entities, and various development partners to promote and advance the technology [17,18]. These technologies are well-suited to small-scale, household applications, generally constructed using locally available materials, fed with typical agricultural and household waste [19], and built at a relatively low cost [20]. However, for many, the cost of installing a biogas digester, which ranges from USD 600 to 1000, is prohibitively high for many low-income households, especially where access to financing and credit options is limited [21,22]. This is especially challenging with the lack of government support and the widespread availability of free or low-cost firewood as well as a shortage of trained technicians who can install and maintain biogas systems, which affects the reliability and efficiency of these systems [19,21].

As outlined by GIZ [23], Uganda has a significantly underdeveloped policy and regulatory environment for supporting renewable energy development (including biogas), the current policy environment includes: the Energy Policy [24], aiming to create a financially sustainable electricity sector without subsidies (competed in 2012), the Renewable Energy Policy 2007 [25], aiming to increase the use of renewable energy sources to 61% of the total energy consumption by 2017, and the Vision 2040 [26], which recognises the importance of technological energy choices in the context of climate change. Whilst all these targets are yet to be achieved, the promotion of biogas and other renewable energy technologies, through subsidies, tax incentives, and public awareness campaigns, continues to move slowly towards 2030.

The biogas sector in Malawi is currently in its early stages; however, there are indications of an increasing willingness to adopt new technologies to meet cooking demands due to the rising costs of charcoal and firewood [27]—which is in contrast to the rest of the clean cooking sector which has seen significant stagnation, with only 1% (as of 2022) of the population having access to clean cooking fuels and technologies [28]. One indicator of this positive movement is Sistema.bio's (Swiss-funded) carbon finance program in partnership with EcoGen Malawi to deploy 10,000 biogas systems in Malawi to reduce the financial burden to users by providing more flexible financing and low-cost financing [29]. Despite these efforts, the issue of affordability and acceptability remains a key barrier to the adoption of biogas technology, especially as the policy and regulatory environment does not directly support biogas despite it being included in Malawi's NDCs. For example, biogas systems and components are not yet included in renewable energy customs duty, excise tax, and VAT exemptions, as per the 201 Customs and Excise (Tariffs) Order, there is a "zero rate of VAT on LPG gas and cylinders, solar equipment, and wood cookstoves; and removes customs duty and excise tax on LPG cylinders" [30].

1.1. Exploring the Energy Access, Anaerobic Digestion, and Smart Metering Nexus

The fragmented nature of the biogas sector meant that these potential impacts have been plagued with issues of system failures and abandonment [14]. There has been a missing element between energy access and AD that ensures the longevity of these systems. The introduction of the "Internet of Things"-enabled low-cost, remote monitoring devices has the potential to connect this fragmented energy sub-sector. Robinson et al. [11] present the state-of-the-art for the intersection between energy access, AD, and smart metering. They state three key dimensions of remote and smart metering: improved user experience, enabling biogas-as-a-service, and the integration of remotely monitored data for real-time carbon financing. The structure of the following section follows these three key dimensions.

1.1.1. Improved User Experience

Farmers, communities of people, institutions, and small businesses who build, operate, and maintain biogas units across Sub-Saharan Africa are all constrained by one simple fact: they cannot physically see inside their biogas digesters. Without specialised knowledge and training, which links the relationship between pressure and feedstock, it leaves users thinking their digester is a "black box" of information. This results in end-users making use choices, i.e., what they use the gas for, based on limited information, and they often do not use the full potential of the gas or digestate production. Through the digital monitoring of these digesters, primarily through flow and pressure data, significantly more detailed insights can be generated for end-users that can significantly improve their experience [11]. When there is a higher level of digital and biogas literacy, this opens the possibility of connecting with the productive use of energy (PUE). Kapadia [31] provides a foundational definition of PUE as "utilization of energy—both electric, and non-electric energy in the forms of heat, or mechanical energy—for activities that enhance income and welfare". Terrapon-Pfaff et al. [32] further categorise PUE based upon the energy needs of electrification, food preparation and conservation, farming tasks, cooling, and lighting; however, Terrapon-Pfaff et al. [32] are quick to state that "access to sustainable energy does not automatically result in productive activities and that energy is only one of the input factors required to foster socio-economic development [...] training, equipment or market research—need to be an integrated part of the energy project itself to allow for productive activities to develop on a wider scale". As the scales of implementation change, these end-users cover people operating biogas systems (farmers, communities of people, institutions, and small businesses) and the data uses (such as for PUE) additionally evolve—we explore these specific evolutions further in this paper.

1.1.2. Biogas-as-a-Service (And PayGo)

Whilst in the case of improving user experience through increased data access, essentially only the end-user has access to this data (and potentially the company providing the digital meter), the biogas-as-a-service model opens the data access to a potentially wider number of stakeholders. The biogas-as-a-service model is based on the energy-as-a-service model, which is "a business model whereby customers pay for an energy service without having to make any upfront capital investment" [33]. This service can be extended past energy provision to "energy advice, asset installation, financing and energy management solutions to offer a suite of services to the end consumers" [34]. Typically, there are two models of biogas-as-a-service which depend on the scale of the biogas digester. Household systems biogas-as-a-service models look to unlock use-based financing to reduce the financial burden to customers, whereas on the community and commercial scale (where a company owns the AD system), it is a method of creating access to biogas with the customers or end-users having no financial risk.

As the biogas-as-a-service sector is still very nascent (with foundational practical examples being shared in this paper) we can draw learnings from other sectors who developed energy-as-a-service models which are enabled by digital remote monitoring technologies. For example, Shupler et al. [35] outline a typical PAYG model for LPG, "the customer is provided with the equipment (regulator, hose, stove and cylinder with smart meter) for a small upfront cost. The customer can then purchase LPG credits in small increments (via mobile banking) which allows for a corresponding amount of gas to be released from the smart meter; there is usually a surcharge (~5–10%) to the fuel costs to cover PAYG LPG equipment installation and delivery fees". In this case, PAYG has been implemented across informal settlements in Kenya and resulted in significant gendered, financial, and nutritional benefits. However, this system is possible with LPG as the initial capital cost of the system is small and can be easily recovered if payments are not made. In the case of biogas systems, especially the fixed-dome type, these are built into the ground and thus are immensely challenging to recover. In addition, recovered biogas assets—be they fixed-dome or bag-type—have limited resale value for the biogas company. There is a significant ethical implication in turning off or recovering the system in cases where modern, sustainable, and reliable energy access is limited—by removing the asset, the recovering company is forcing the customers to backslide to a significantly more polluting, unhealthy, and time-consuming cooking technology.

Depending on the owner of the system, be it a private company or community organisation, the biogas-as-a-service model can unlock additional operational models that can potentially democratise energy systems [36], resulting in more inclusive business models, as suggested by EnDeva [37] in their inclusive business framework. There is then the potential to explore different ownership models, especially around maintenance—"the paper concludes that, institutional arrangements for communally owned mini-grids need a collective interactive approach among local users for sustainable mini-grids maintenance" [38]. The next step would then be to use user-owned decentralised smart grids, or local smart energy systems, however, as outlined by Bray et al. [39] in the European context, these local smart energy systems have both significant co-benefits and limitations.

1.1.3. Digitally Monitored and Remotely Verified Carbon Finance

Digitally monitored and remotely verified (dMRV) methodologies for carbon financing build on the ability of IoT-enabled, remote monitoring meters to gather large volumes of use data and often leverage blockchain technology for remote verification. In a time where the carbon market has seen significant transparency and accountability issues—widespread overcrediting of manually verified credits [40] and alleged large-scale carbon fraud by CQuest Capital (one of the largest issuers of credits) [41]—dMRV may provide one method of regaining the sector's trust [42]. In 2022, Gold Standard launched the standardized "Methodology for Metered and Measured Energy Cooking Devices", which covered the dMRV of LPG, electric, biogas, and bioethanol cookstoves [43] and updated the "Methodology for Animal Manure Management and Biogas Use for Thermal Energy Generation" to cover digital monitoring [44]. The digitalisation of the small and medium-scale biogas sector coupled with the new Gold Standard methodology, and the large carbon offsets biogas generates when compared to cooking over an open fire, opened a pathway for dMRV methodologies in the biogas sector. Whilst there are existing projects in the biogas sector which leverage manual verification processes to provide more effective after-sales services and reduce initial capital costs of the biogas digester [45], the CAVEX project leads the sector with its dMRV approach which looks to "revolutionise the voluntary carbon market by allowing small producers of carbon credits such as farmers and small businesses to sell directly to corporate buyers" [46].

Whilst dMRV methodologies overcome many of the challenges of the traditional or manual verification process, there are still a number of key considerations for dMRV methodologies when considering international development projects which look to build fair, just, and equitable programs [11,47]. For example, dMRV methodologies typically decrease monitoring costs over the long term—in the case of the SB meter, this payback period is up to 4 years depending on the carbon price [48], increasing the profitability of credits. The question then becomes, what is the appropriate approach to sharing these increased benefits? ATEC's "Cook to Earn" pilot looks to directly pay users, after digital verification, through mobile money for using their induction stoves—the rate of this payback is determined by ATEC [49]. Climate Action Platform Africa [50] outlines several other benefit-sharing techniques, including technology subsidies, in-kind contributions (such as infrastructure building), payments into community funds (formal or informal microfinance), and direct cash payouts. Additional challenges exist around data security, transparency, and validation [51], especially the enforceability of these data challenges across international borders. In addition, there are several other credits or tokens that are relevant for biodigesters. Building on the work of organisations such as ixo [52], biodiversity, water quality, peace, and renewable energy credits all have significant relevance to biodigesters.

1.2. Research Aim, Objectives, Novelty, and Significance

Building on previous work [11,14], in this paper, we aim to develop and explore the multi-scale nature of AD system delivery models and understand how these different scales of implementation can unlock meaningful pathways to the completion of SDG7. This aim is realised through three key objectives:

1. To understand and establish the state-of-the-art in biogas delivery models and implementation strategies across multiple scales.
2. To explore three delivery models based on case studies generated as part of the InnovateUK Energy Catalyst "Smart Biogas 3: Digesting Data" project through a mixed-methods approach.
3. To compare, contrast, and evaluate these three delivery models and to provide key themes for practitioners and academics to take forward this work.

The novelty and significance of this paper is three-fold: First, establishing the connection between AD systems for energy access and the wider delivery model literature from the energy access sector. Second, focusing on multiple scales of AD system delivery models, especially the interconnected nature and relevance to meaningful energy access pathways across larger-scale systems. For example, clean cooking in institutions and enterprises has seen disproportionately little attention when compared to the household and community levels [29,53,54], and larger-scale AD systems are significantly underutilised [55]. Third, the integration of smart monitoring technologies and the value that this type of monitoring technology brings across multiple scales of delivery model. Within the commercial scale, existing work, such as that by Kemausuor et al. [55], provides examples of commercial systems and their contextual variations, but does not consider the digitalisation of these units and the effect that this digitalisation has on the delivery model. This means that this paper provides foundational knowledge which can be of use to practitioners and academics in their future work. By drawing on real-world examples of AD delivery models, this paper proposes a novel entire ecosystems or systems approach to biogas implementation through the blending of different scales of implementation.

2. Methods

This section presents the SB3 project and the data collection and analysis methodology. The data collection and analysis consists of two phases. Phase 1 is an in-person participatory market systems development workshop in Lilongwe, Malawi, designed to develop market maps for household and community-scale biogas systems and services. Phase 2 leverages expert knowledge of the Uganda and Malawian biogas sectors to develop case studies that illustrate the three scales of AD system delivery model.

2.1. Data Collection and Analysis in Two Modes

2.1.1. Participatory Market Systems Development Workshop in Malawi

As outlined by Practical Action's detailed documentation [56], participatory market systems development (PMSD) workshops are a tool "to provide a space for market actors to understand how their market system really works. This enables market actors to better understand their interdependency and the economic opportunities that exist from greater cooperation. As no single market actor understands the market system in its entirety, this is more effectively achieved through bringing together a variety of market actors who all share their different perspectives". It relies on four core principles—facilitation, participation, systems thinking, and gender—for its effective implementation [56]. In this case, the PMSD workshop was conducted to identify existing and new biogas delivery models within the Malawian context.

In November 2023, the University of Nottingham, Inclusive Energy, and Green Impact Technologies Malawi (GIT) gathered the leading biogas experts from the Malawian sector to engage in a participatory market systems development workshop to: (a) understand and map core processes in Malawian small and medium-scale biogas market to better understand the sustainability and productive user/commercialisation of biogas, (b) build connections to and trust with the key stakeholders leading to collaborations that unlock new pathways of working, and (c) identify new project opportunities for project partners. The participants of this workshop included biogas manufacturers, suppliers, and users, as well as the relevant government officials responsible for biogas (and the broader biomass sector). Participants were both encouraged to contribute from their perspectives in the biogas sector and listen to others who may share different perspectives. Within the workshop, there were five core sessions designed to understand, draw, analyse, and explore the Malawian biogas sector. These included (1) an introduction to SB3 and the PMSD process, (2) games around market map development, (3) identifying key challenges/opportunities from multiple stakeholder perspectives within the generated market map, (4) exploring the smart biogas (SB) meter and its effect on the market map, and (5) engaging with end-user productive use. The data produced in this workshop provide the basis for the medium-scale delivery model within the Malawi biogas context.

2.1.2. Delivery Model Case Studies: Uganda and Malawi

The delivery model concept, linked to the need to ensure the financial sustainability of energy projects and programs, gained significant traction in the humanitarian [4,57] and wider international development [3,58] energy sectors. To streamline the development of delivery model case studies a delivery model framework was developed drawing from the available literature. Across the literature, there is a diversity of potential dimensions; for example, EnDev [57] approaches the topic with a case study approach through key achievements, innovative aspects and drivers of success, main encountered barriers, and the (enabling) environment. Whereas Bisaga and To [4] talk of the critical dimensions of successful delivery models in the HE context, such as innovative business models (such as PayGo and lease-to-own) and innovative financing mechanisms (such as results-based financing). On a more foundational and theoretical basis, Bellanca and Garside [3], and the subsequent Energy Delivery Model toolkit [59], build on Osterwalder's Business Model Canvas [60] and the Delivery Model Map [61] to develop the Delivery Model Canvas. This framework is comprised of the delivery infrastructure (key activities, key stakeholders, key resources), value proposition, end-users (target groups, ways of doing outreach and delivery, relationship with end-users), and accounting (revenue streams, cost structure, other costs/benefits). Drawing on these elements, we developed the framework in Table 1.

Table 1. Framework for delivery model case studies.

Factor/Dimension
Hyper-specific context overview
Size and type of biogas unit
Overview of delivery model—including business and financing model
Stage of implementation
Main encountered barriers
Enabling environment (specific policies and laws, infrastructure, institutions, global trends, or natural resources that are needed)
Additional supporting services (awareness campaigns, micro-finance, lobbying, capacity building, startup grants, and credit)

Based on the above framework in Table 1, the case studies were developed with and by the Ugandan and Malawian project partners in each country through a series of consultants both in person and online. These project partners are the key biogas experts in these biogas contexts and lead much of their respective sectors. In addition to the delivery model case studies, we looked to provide contextual variations of these models drawing from the available literature.

3. Results and Discussion

The findings and analysis section is divided into two sections. First, a presentation of three scales of implementation, and second, a comparative analysis of the three scales of implementation and their contribution as a potential pathway to the completion of SDG7. This section is generated from the PMSD workshop in Malawi and the expert consultant sessions.

3.1. Results: Scales of Implementation and Associated Models

As identified in the literature review, smart and remote metering unlocks three key dimensions: improved user experience, increased access to financing, and the possibility to integrate carbon financing. In this section, we present three key scales of biogas systems and their associated delivery models, integrating and exploring these three dimensions. These three scales are the household scale in Uganda, the community scale in Malawi, and the potential for commercial scale in Uganda. In each case, we address the importance of digitalisation for the successful and sustainable implementation of these systems.

3.1.1. Household-Scale Delivery Model: PayGo in Uganda

A critical barrier to the wide-scale adoption of household scale systems in Uganda is access to and willingness to finance these systems. Biogas Solutions Uganda Limited (BSUL) designed a delivery model that, in combination with a low cost, the SB meter transparently connects the pre-financing of biogas systems (through a revolving fund) to biogas enterprises (BEs) and potential new customers. Figure 1 provides a graphical overview of the delivery model and its key components, Figure 2 outlines the accompanying financing process, and Table 2 provides the details of this model. This delivery model means that financial institutions can more safely extend biodigester loans to farmers or BEs in a market where financing for biogas is limited.

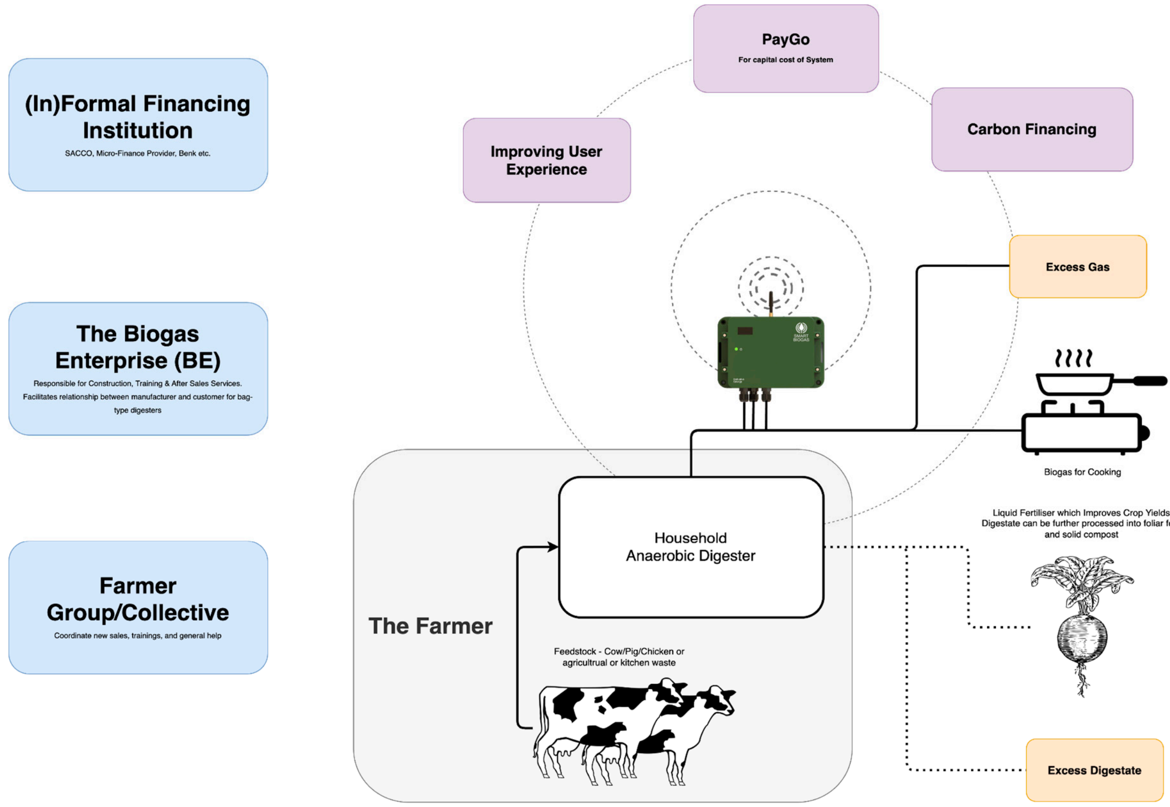

Figure 1. Typical smart-metered household-scale biogas system (authors).

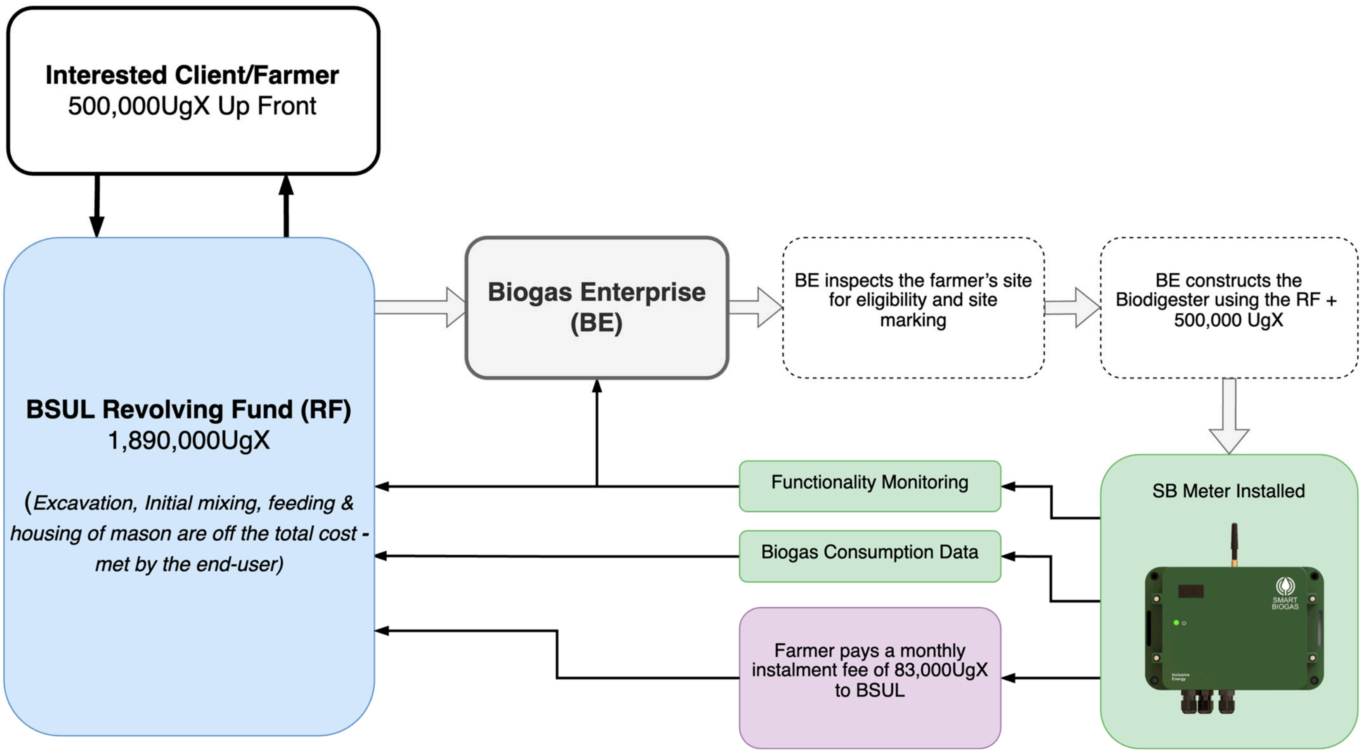

Figure 2. Capital flows for Uganda PayGo model at household scale (authors).

Table 2. Household-scale system delivery model in Uganda—smart biogas meter and PayGo.

Dimension	Household-Scale System Delivery Model in Uganda—Smart Biogas Meter and PayGo
Implementation context	Busoga sub region-Eastern Uganda (Jinja and Buikwe districts)—an area with higher poverty rate and low biodigester intake when compared to other regions.
Size and type of unit	4–9 m^3 fixed-dome bio-digester
Overview of delivery model	This delivery model develops a PayGo system using the SB meter to spread payment over a 1–2-year period. Farmers must make an initial payment of UGX 500,000 (USD~135) and cover the cost of excavation, initial mixing/feeding, and housing for the mason. The digester construction is pre-financed by BSUL's revolving fund and constructed out by a Biogas Enterprise (BE). Monthly payments are fixed at UGX 83,000 (USD~22) until the full cost of the digester is returned to BSUL revolving fund. In addition, this model: - gives farmers confidence through real-time fault monitoring, - increased after sales services from BEs through monitoring data, - and increased quality assurance thus derisking loans for financial institutions and BEs. This increased transparency contributed to an improved relationship between the service provider, the farmer, and the loan agency or microfinance.
Stage of implementation	Eleven farmers so far benefited from the PayGo program (with a payback period of 1–2 years). BSUL and KASECO are conducting follow-up training with farmers to guide on bioslurry utilisation and bio-digester operation. KASECO built capacity in designing a PayGo program and as a BE it is planning on supporting an additional two farmers per quarter to help farmers overcome the limiting initial upfront costs.
Main encountered barriers	- Inconsistent monthly instalment payments by the farmers due to seasonal incomes tied to agricultural production. - BSUL's limited pre-financing capital through SB3 in the revolving fund—more capital results in more BEs and farmers supported as well as faster returns into the fund.
Enabling environment	- Ban on charcoal production in the northern region by the presidential executive order increased the price of charcoal and favoured the uptake of technologies such as biogas [62]. - Launch of the Electricity Access Scale up Project that offers a direct subsidy to end-users to influence the biodigester demand [63]. - Low-interest loans provided by UECCC to farmers to boost biodigester uptake [64] and presence of green loans in equity banks to support renewable energy startups and farmers [65].
Additional supporting services	Training to both farmers and BEs to create awareness, identify emerging opportunities, and offer guided after sales services.

3.1.2. Community-Scale Delivery Model: Biogas-As-a-Service in Malawi

This community-scale delivery model leverages the "energy-as-a-service" approach to provide gas and liquid fertilisers to farmers, households, and restaurants on a contract or service basis. This is possible through the transition of ownership, operation, and maintenance of the digesters to a central organisation, typically a BE, mitigating many of the issues of household-scale systems with knowledge erosion, operation and maintenance, and low-quality construction of systems [14]. Unlike the household scale, the community-scale delivery model significantly reduces the financial risk and training burden for end-users (farmers or customers). However, this is ultimately a more complex market system; key notable differences compared to the household scale are in the role of suppliers—as these organisations have multiple clients (digesters and equipment to the central managing organisations, and biogas stoves, backpacks, and piping to end-users)—the feedstock value chain, and the importance of smart monitoring for "biogas-as-a-service". As is the case with all AD systems producing outputs for sale, the availability of feedstocks is the critical component in optimising the production of gas and liquid fertiliser. This means that a feedstock value chain must be actively created, which may include situating the digesters close to markets for food waste, slaughterhouses for animal waste, or agricultural sites (such as gain millers) for agricultural waste—this value chain tends to perform more effectively for B2B rather than end-users supplying feedstock. As with any other new approach or market system, the right blend of policy and regulatory tools, organisational skills, and implementation environment must all come together as in Figure 3 and Table 3.

Table 3. Community-scale system delivery model—biogas-as-a-service.

Dimension	Community-Scale System Delivery Model—Biogas-As-a-Service
Context overview	Community-sized biogas systems are well suited to Ntcheu's Tsangano Turnoff because of its strategic location as a bustling marketplace that links Malawi and Mozambique and it has an abundance of agricultural and slaughterhouse waste. Plus, it is a thriving market palace with many use cases for biogas and digestate.
Size and type of biogas unit	A Puxin 15 m^3 flex biogas system.
Overview of delivery model	This system (owned by GIT) supplies biogas to connected businesses (and potentially physically close households) via a network of pre-financed pipes leading directly to kitchens via a smart meter. The private sector company (in this case, Malawi private sector partner) is responsible for the operation and maintenance of this system (identifying technical issues through the SB meter and online developer platform). The income streams of this delivery model are as follows: - The businesses act as anchor clients who regularly use and pay for biogas through a PayGo enabled SB meter. - The households are secondary customers who access gas either through the biogas backpack or directly piped (and SB metered) into their kitchens. - Selling liquid digestate to farmers groups at a significantly reduced cost when compared to government subsidised chemical fertilisers. - Transforming excess biogas into electricity (which is stored in batteries) for the charging of small electronic devices.
Stage of implementation	The biogas project is in its early implementation phase, with several initial commercial projects under construction.
Main encountered barriers	- Higher capital investment associated with setting up large-scale biogas digesters. - Maintaining a consistent supply of organic waste and variability in feedstock availability. - Regulatory hurdles: delays in obtaining necessary permits, market development challenges, and substantial effort to build demand for biogas and its byproducts. - Technical issues, particularly related to biogas pressure from backpacks when cooking.
Enabling environment	- Malawi's National Energy Policy [66] creates an atmosphere that is generally favourable to the expansion of biogas and other renewable energy projects. - Grid connection infrastructure is necessary for integrating biogas-generated electricity into the existing power grid, making it accessible to users.
Additional supporting services	- Awareness campaigns for potential users about the benefits and opportunities of biogas systems. - SME finance options (including grants and low-interest loans) and startup grants can help lower the financial barriers for larger-scale systems. - Capacity building is crucial for training skilled labour to operate and maintain the biogas systems effectively. - Market promotion efforts are needed to create demand for biogas and its byproducts, helping to establish a stable market for both the biogas and biofertiliser products.

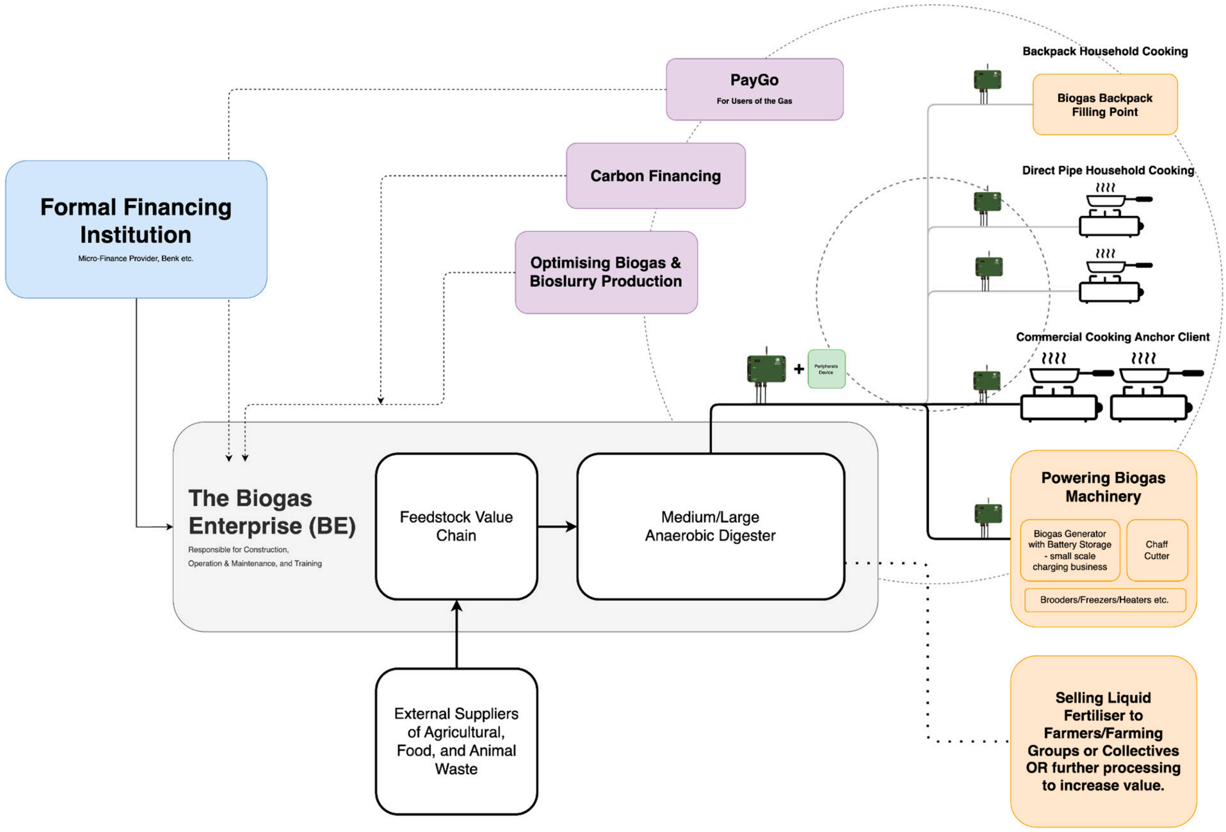

Figure 3. Community-scale smart-metered biogas system (simplified from Malawi PMSD workshop).

3.1.3. Commercial-Scale Delivery Model: Leveraging a New Approach in Uganda

The SB3 project directly focuses on the household and community scale systems (with their accompanying delivery models). As part of the work for this paper, we looked to expand this focus to commercial-scale systems that were manageable within the current East African biogas ecosystem. However, identifying 'real world' case studies that sit in between the community (20–150 m^3) and large-scale commercial units seen across Europe (1000 m^3+) was a significant challenge. Often, when talking about larger-scale systems, the systems themselves were scaled but the delivery models were the same as smaller typical household or community scales with a significant (over)reliance on productive use to increase the gas usage—we discuss this further in the comparative analysis of delivery models later in the paper—rather than a focus on B2B customers, such as bioenergy entrepreneurs, gas companies, and electricity suppliers [67]. However, it is not only the increased production of gas that occurs when using larger-scale systems, a significantly increased volume of digestate is also produced. There are significant benefits in looking beyond digestate as a way to increase crop yields or as an insect repellent or to engage with the contemporary research around cosmetics, as explored by the National Agricultural Research Organisation Uganda [68]. This presents new channels for raising income through utilising bioslurry more efficiently. The biogas market in Uganda is well established at the household and small-scale farm level, though relatively little focus has been given to the potential benefits of digestate specifically. Beyond some striking outliers, underuse, misuse, or general ignorance around bioslurry is common amongst many users. The authors' experience highlights three significant issues: first, the larger commercial-scale AD systems are required, and second, a structured and equitable logistic plan for the transportation of digestate between producers and consumers requires consideration to ensure that the opportunities for market development are realised. Lastly, greater levels of education are needed for biogas system owners and operators as concerns the future opportunities afforded to digestate producers. Figure 4 presents a visual representation of a system that overcomes these challenges, and Table 4 outlines the details of implementing such a model in Uganda.

Table 4. Commercial-scale system delivery model—large-scale energy production.

Factor/Dimension	Details of Commercial/Large-Scale System Delivery Models
Context overview	The context is broadly similar to the household case study; there may be additional benefits for this model in peri-urban or urban centres due to the significant volume of feedstock that would be needed to sustainably power these large-scale digesters.
Size and type of biogas unit	150 m^3+
Overview of delivery model	This system is owned and operated by the biogas enterprise, it is financed through commercial financing (loan or debt financing) typically available for larger-scale energy projects—the smart meter significantly increases the efficiency of this operation. There is additional potential for government subsidies if electrical generation occurs (connected to regional/national grids) or large carbon + biodiversity financing offsets are made. This model is made possible by the larger digester sizes and gas production volumes, distributing the cost of biogas bottling and cleaning technologies over a larger customer base. Income streams: - Direct transmission to regional/national grids. - Indirect transmission to local grids (electricity supplied by biogas generators through bottled biogas). - Selling bottled biogas to consumers. This gives this model access to the entire LPG market—bottle biogas provides an ecological alternative to LPG and possibly at a lower cost point due to the less energy-intensive nature of gas extraction and being a byproduct of a waste stream. - Biofertiliser sales. - Biofertiliser post-processing into products such as skin case and washing products.
Stage of implementation	Theoretical delivery model developed for Ugandan context.
Main encountered barriers	Typical expected barriers in Ugandan context: - Feedstock: a separate feedstock value chain would need to be established to generate the required volume of waste. - Initial capital investment of biogas cleaning and bottling technologies is significantly larger than typical community or household-scale systems. - Regulatory barriers as the model may see biogas company as an energy developer—falling under another set of regulations around electrical generation.
Enabling environment	As in Table 2.
Additional supporting services (inputs and services)	- Training on bottled biogas and how it differs from conventional LPG. - Awareness campaigns for potential users about the benefits and opportunities of biogas systems. - Market promotion efforts are needed to create demand for biogas and its byproducts, helping to establish a stable market for both the biogas and biofertiliser products.

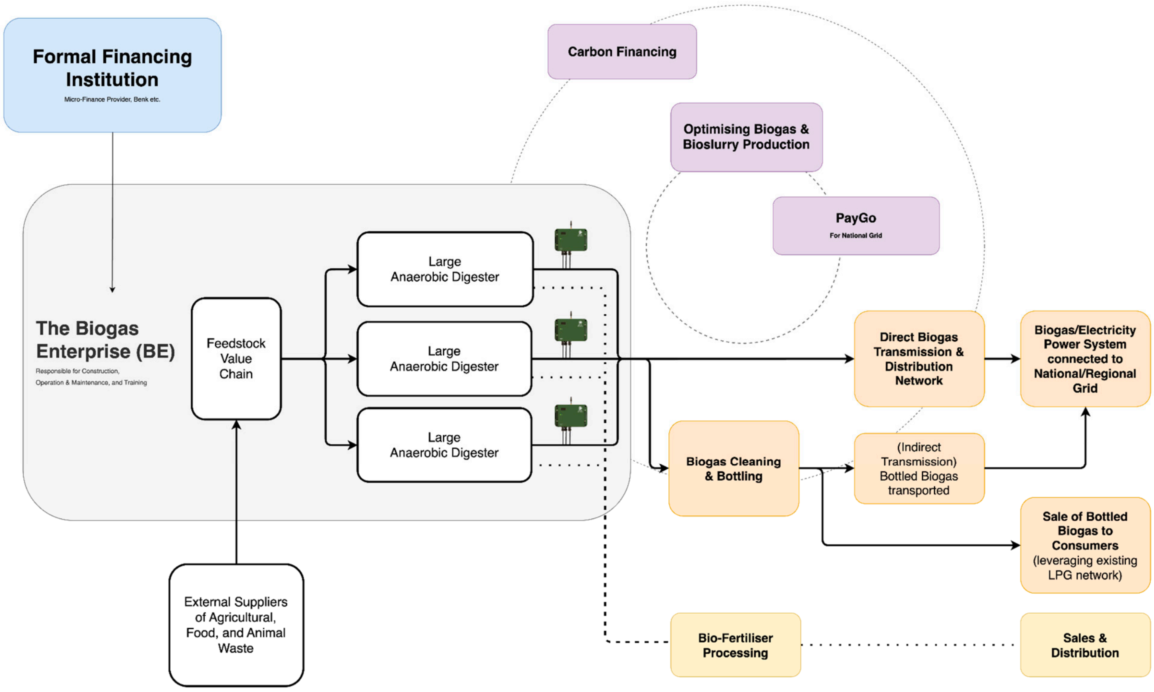

Figure 4. Commercial-scale smart-metered system.

3.2. Discussion: A Critical Examination of Delivery Models

In the previous sections, we presented a series of case studies to illustrate the diversity of delivery models within the biogas sector across Uganda and Malawi. Within this section, we critically examine the three scales of delivery models—household, community, and commercial—to present several cross-cutting themes which emerged from this work.

3.2.1. Increasing Digester Size Does Not Always Mean Delivery Model Scaling

Throughout the energy access literature, there is a recurring theme: the productive use of energy will increase the affordability of energy systems and services as people can generate income from these systems [32]. Many practitioners across the clean cooking and wider energy access sector make this concept a cornerstone of their identity and programming [31,69–72]. The underlying assumption is that energy access results in productive use. However, this is not the case; to paraphrase Terrapon-Pfaff et al. [32] in the literature review, productive use must be an integrated part of the energy project itself and not an addition. The realisation of the importance of PuE to practitioners resulted in a realisation within this work that there is a disconnect between how practitioners talk about the size of biogas digesters and the scale of the delivery model. As illustrated in Table 5, biogas programs often scale the size of the digester, but exclusively rely on PuE to make up the gas usage requirement for larger-scale units—as documented by the Robinson et al. [73], this is often in places where there is no market support for these biogas-powered appliances. Additionally, Robinson et al. [73] states that when digester size is mismatched with gas consumption, venting occurs, which has a significantly under-documented impact on global methane (and carbon equivalent) emissions. Whilst the household-scale systems above 20 m^3 rely heavily on PuE as a secondary use case, PuE is at the heart of the community and commercial models. This centrality rather than additionality means that many of the activities stated by Terrapon-Pfaff et al. [32] become central to the success of the business and thus a critical investment for organisations running these systems. Table 5 highlights the relationship between the size of digester and the delivery model (for the primary use case, there are additionally secondary and tertiary use cases which blurs the lines between these models). Moving left to right on rows scales the size of the digester (and keeps the business model and accosted ecosystem (type of finance, construction, training, operation and maintenance, etc.) the same), moving top to bottom scales the delivery model (and thus business model).

Table 5. Size of digester vs. delivery model.

Delivery Model	Key Characteristics of Primary Use Case	Size of Digester and Delivery Model Financial Viability (Tick/Cross)		
		5–12 m^3	20–60 m^3	60–150 m^3
Household (C2C)	Owned by institution/single user Gas and digestate used at source Feedstock from site/kitchen PuE for excess gas (on site utilisation) Sells/gives excess gas and digestate to neighbours	✓ Small-scale farmer	✓ Institutional scale	✓ Large-scale farm
Community (B2C)	Owned, operated, and maintained by biogas enterprise Feedstock collected/bought form community Sells gas/digestate to private customers or anchor client PuE integration for increased profitability	✗ No cost recovery	✓ 1 anchor client	✓ 3+ anchor clients
Commercial (B2B)	Owned, operated, and maintained by biogas enterprise Sells gas to commercial entities/national electricity grid Bottling plant for biogas Further processes digestate into solid fertilisers Feedstock value chain established	✗ No cost recovery	✗ No cost recovery	✓ Minimum viable size

3.2.2. Overcoming Delivery Model Weaknesses Through Blended Approaches

The multi-disciplinary and intersectoral nature of energy production and consumption results in diverse and changing energy needs. As outlined by MECS et al. [29], the landmark scaling clean cooking report launched at COP29 on behalf of the Africa Union, which means an entire systems approach is needed that reacts to the diverse energy needs of individuals, and hence these different models must not be treated as mutually exclusive, but complimentary. The disconnect between the size of the system and the delivery model in the previous section could indeed be a strength in unlocking a "basket of solutions" which enables cooks to choose their cooking technologies depending on their real-time and evolving cooking needs. This requires a suite of systems and services that stretch from improved cookstoves to biogas and electric cooking. What are then the specific complementary dimensions of these three delivery models?

The critical challenge with the household model, across the multiple sizes of digester, is the capital investment required by an individual to install their anaerobic digester. This is well documented in the literature and often attributed to seasonal and varying income, access to formal and informal finance, and willingness to invest [74,75]. The community model overcomes this barrier by providing PayGo access to biogas or digestate through direct piping (and smart metering) or through biogas backpacks; there are also additional benefits, such as the biogas enterprise being responsible for the operation and maintenance (overcoming failure and abandonment issues with such technologies [14]) and the financial burden of purchasing the system being with the biogas enterprise. However, the community model, and indeed all larger-scale biogas units, face challenges with sustainable feedstock sources. Unlike the household model, where the owner of the system also typically owns animals which feed the digester (see sales practices from Systema Bio. [76]), community-based models must source the feedstock from the surrounding communities. In the Malawian case study, this is achieved by positioning the unit close to a slaughterhouse and large bi-weekly market. Whilst these feedstocks are currently free, participants of the PMSD workshop shared concerns that when community members see these feedstocks producing value for the biogas enterprise, this relationship may change and thus make the model less affordable for the community. The commercial model understands this challenge and looks to create a market for this waste to achieve the volumes required for large-scale biogas production. These commercial-scale systems also open a wider variety of commercial waste streams, although commercial waste already has existing commercial waste markets. The feedstock value chain may require commercial systems to be in centralised locations (rather than community and household systems where gas/digestate is consumed close to the point of production) which are connected to transport infrastructure, thus the need to explore a more diverse range of distribution technologies such as bottling or selling energy into the existing regional or national grid infrastructure. In this case, end-users see a benefit from access to bottled biogas/electricity as well as the selling of waste that would otherwise be unused or not seen as an opportunity for income generation.

3.2.3. The Role of Digitalisation

The results of the rapid review identify three dimensions to the state-of-the-art: improving end-user experience, PayGo functionality, and carbon financing. These dimensions are applied differently across the three delivery models—Table 6 outlines these potential impacts. Simply, the household model is significantly enhanced by this digitalisation and the community and commercial delivery models would not be possible without the comprehensive insights shown by IoT-enabled enabled smart meters (as outlined by the barriers to commercial-scale biogas systems in Africa by Kemausuor et al. [55])

Table 6. Digitalisation across the three delivery models.

	Improving End-User Experience	**PayGo Functionality**	**Integrated Carbon Financing**
Household	Gives users access to data to optimise their system through changing feeding schedules, reduce venting (Author, 2025) linked to climate emissions, and quickly identify hardware failures. Reliance on PuE required detailed and precise information, being able to make informed decisions between use cases, i.e., can I also cook a meal if I use this gas to power a chaff cutter or sell 1 kg of gas to my neighbour? For example, a school in Malawi using approximation to gas production (when gas runs out).	Enables users to reduce the financial burden and spread payments over a longer period. This dimension helps strengthen the case when discussing the balance for households between the investment required to digitalise and the benefits that they see from this digitalisation.	Increased cost efficiencies of carbon financing for household digesters [48]. In Kenya, this results in lower digester installation costs [46] and increased after sales support and training from biogas technicians.
Community	Allows the biogas enterprise to increase the efficiency of their production unit with limited technical experience of the AD process.	Provide tailored payment plans to customers based on real-time use rather than standard monthly payments. Enabled financial institutions to track productivity of systems for repayment of loans.	Cover the operational and maintenance costs of the digester thus reducing the cost to customers.
Commercial	The end-user being the commercial biogas enterprise to the efficiency of their production. In addition, extensions such as Inclusive Energy's peripherals device allow commercial organisations to customise the parameter which they are measuring.	Whilst this dimension is less useful, it does enable the commercial biogas enterprise to directly sell gas to customers.	Contribute to the operational and maintenance costs of the digester, thus reducing the cost to customers.

However, uncritical acceptance of these new ways of working does risk reinforcing many of the structural challenges associated with previous models of development; exploitative practices of researchers and the research [47], the prioritisation of real energy needs in the context of a just transition [77], and systems which reflect the colonial models of development [78,79], as well as forcing commercial organisations to often choose between people, profit, and planet [80], to name a few of many.

3.2.4. The Importance of Tailoring Delivery Model to Country Context

The final theme is centred around the importance of tailoring the delivery model to the complex implementation context; this means both the socio-cultural, environmental, and financial context of the BE and customers or end-users, but also the policy and regulatory environment. We highlight several contextual variations drawn from the authors' experience and the literature.

Contextual variations in household-scale delivery model: The household model is the standard for many biogas programs across the globe. This approach, championed by SNV, and the current African Biogas Component Program [18], develops one very effective mechanism for larger biogas dissemination and provides the basis of a sustainable business model for households [81]. This model sees contextual variations across sub-Saharan Africa which are dictated by the specific policy and regulatory environments as well as the maturity of the local biogas sector. For example, whilst the Kenyan household-biogas sector has a broadly similar core user group when compared to Uganda—rural and peri-rural farmers—there are significant variations in the delivery models due to the strong policy and regulatory environment which encourage biogas systems and resulted in the installation of significantly more units. This additionally enables innovations in household-scale digester design; for example, SimGas's HDPE modular biogas units which allow customers to scale their units depending on their energy needs [82]. This contrasts with Malawi, where there is a focus on bag-type digesters rather than the fixed-dome types in Uganda. In this case, the system manufacturers are typically international organisations which promote bag-type digesters (Sistema.Bio as one example). These organisations do not have a physical presence in Malawi and operate through local suppliers who are, in effect, responsible for the local value chain (in the case of Sistema.Bio, this is ECOGEN). These local suppliers coordinate the installation of units and provide end-user training and after-sales support. In addition, and in contrast to Uganda, the excess bioslurry is more commonly sold to other farmers to supplement their government-subsidised fertiliser bags at a significantly lower cost than chemical fertilisers. These farmers then form cooperatives as a method of streamlining training practices.

Contextual variations in community-scale delivery model: In a different Uganda context, one farmer's cooperative in the Butebo district secured funding from a community leader for the construction of a communal 30 m^3 biodigester from which biogas would be generated and shared among the farmers using biogas bags of 1 m^3 and 2 m^3. This communal model shares many similarities with the community-scale delivery model yet enables farmers to contribute cow dung and receive biogas in exchange, calculated at a rate of 0.03 m^3 of biogas per 1 kg of cow dung. However, despite its potential, the initiative faced setbacks due to rat damage to the biogas storage bags.

Contextual variations in commercial-scale delivery model: Whilst developing the commercial-scale model for the Uganda context, we discovered a contextual variation of this model based on bottling in the Indian context. The government of India's 2018 Sustainable Alternative Towards Affordable Transportation (Satat) policy [83] looks to create a marketplace for compressed biogas across India. The favourable nature of this policy resulted in organisations such as Grassroots Energy [84], developing infrastructure to bottle and sell biogas and accompanying research exploring how to facilitate change within this niche market [85].

4. Conclusions

A new generation of systems and services—digitalised AD systems—highlights the interconnected and cross-cutting nature of energy access by evolving delivery or implementation models across the cooking, cooling, lighting, heating, and transport sectors, touching on energy production, distribution, and consumption as well as having a multi-scale (or level) focus—households, communities, and commercial organisations. These AD systems have the potential, when aligned with the socio-cultural, environmental, and financing context, and have the power to generate energy for the long term. Within the context of SDG7, these digitalised AD systems represent a significant opportunity to quickly scale an existing energy technology to meet the massive global demand.

As one component of that larger goal, in this paper, we explored the multi-scale nature of AD systems and services to understand how these different scales of implementation can unlock meaningful pathways to energy access and, ultimately, the completion of SDG7. In line with research objective one, we presented a literature review which highlights three dimensions: improved user experience, biogas-as-a-service, and digitally monitored and verified carbon finance. In addition, we outlined the relevant research limitations. These dimensions ground the subsequent delivery models in the state-of-the-art literature. Next, we present three delivery models: the household, community, and commercial. Whilst the household and community models are based on real-world AD system delivery models, we conceptualised the commercial model based on the authors' deep experience of the Ugandan biogas sector—this addresses our second research objective. The final analysis and findings section provides a critical analysis of the three delivery models in line with research objective three, and we present insights from the case studies which include the disconnection between digester size and delivery model, overcoming delivery model weaknesses through blended approaches to energy access, the role of digitalisation, as well as the importance of tailoring the delivery models to specific contexts. We stress the importance of tailoring the delivery model to the implementation context, as we provide examples of tailoring models to farmer cooperatives in Uganda, the policy and regulatory environment in India looking to create a new market for bottled biogas, and the availability of biogas appliances in Kenya leading to farmers investing in larger-scale biogas units to power machinery. However, as the benefits of AD become more widely accepted, overcoming many of the well-documented barriers, and the outputs (gas/digestate) are utilised across more sectors, the regulatory environment will have to adapt and update.

We see future work in detailed economic modelling of the three delivery models, further categorisation of emerging biogas technologies (such as containerised units), integrating roles of intermediaries and other more informal stakeholders (as seen in work by Dutt [85]), and, as per the wishes of the practitioner authors, evolving the specific delivery models in this paper. Specific future evolutions of the Uganda PayGo model include developing detailed optimisation plans from smart meter data, creating a framework for analysing farmers' or end-users' payment histories before enrolling them in PayGo, and determining flexible payment plans. In the community-scale biogas in Malawi, future work surrounds increasing the value of digestate through further processing into foliar feed or solid compost, enhancing feedstock management by ensuring a steady supply of organic waste, lobbying for supportive policies and regulations that can further facilitate program growth and develop market initiatives to promote biogas products, and providing technical support to biogas technicians to help resolve operational issues and create a more supportive environment for biogas projects.

To end, these three delivery models—the household, community, and commercial—are complementary delivery models that, in combination with other methods of sustainable energy production and use, can provide a suite of technologies that react to the complex (contextually aligned) needs of energy users. However, we recognise that this requires a policy environment that recognises this more "entire systems approach" to energy access. Whilst the competition of SDG7 by 2030 appears as a distant dream, we believe that AD can provide one of many pathways to this goal.

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References

1. United Nations Sustainable Development Goals. Available online: https://www.undp.org/sustainable-development-goals (accessed on 1 September 2024).
2. The World Bank. *Tracking SDG7: The Energy Progress Report*; The World Bank: Washington, DC, USA, 2023.
3. Bellanca, R.; Garside, B. *An Approach to Designing Energy Delivery Models That Work for People Living in Poverty*; IIED: London, UK, 2014.
4. Bisaga, I.; To, L.S. Funding and Delivery Models for Modern Energy Cooking Services in Displacement Settings: A Review. *Energies* **2021**, *14*, 4176. [CrossRef]
5. Stevenson, T.; Willcox, M.; Nash, S. *Can Market Mechanisms Facilitate Energy Access for People Living in Extreme Poverty? Findings and Recommendations*; Practical Action & Kuungana Advisory: Rugby, UK, 2023.
6. IEA. *Defining Energy Access: 2020 Methodology*; IEA: Paris, France, 2020.
7. Gill-Wiehl, A.; Ray, I. Affording a Clean Stack: Evidence from Cookstoves in Urban Kenya. *Energy Res. Soc. Sci.* **2023**, *105*, 103275. [CrossRef]
8. Jewitt, S.; Atagher, P.; Clifford, M. "We Cannot Stop Cooking": Stove Stacking, Seasonality and the Risky Practices of Household Cookstove Transitions in Nigeria. *Energy Res. Soc. Sci.* **2020**, *61*, 101340. [CrossRef]
9. Jewitt, S.; Mahanta, A.; Gaur, K. Sanitation Sustainability, Seasonality and Stacking: Improved Facilities for How Long, Where and Whom? *Geogr. J.* **2018**, *184*, 255–268. [CrossRef]
10. Katuwal, H.; Bohara, A.K. Biogas: A Promising Renewable Technology and Its Impact on Rural Households in Nepal. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2668–2674. [CrossRef]
11. Robinson, B.L.; Clifford, M.J.; Selby, G. Towards Fair, Just and Equitable Energy Ecosystems through Smart Monitoring of Household-Scale Biogas Plants in Kenya. *Energy Res. Soc. Sci.* **2023**, *98*, 103007. [CrossRef]
12. Somanathan, E.; Bluffstone, R. Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change. *Environ. Resour. Econ.* **2015**, *62*, 265–277. [CrossRef]
13. Singh, D.; Tembhare, M.; Dikshit, A.K.; Dangi, M.B.; Kumar, S. Technical and Operational Challenges in Setting up a Decentralized Biogas Plant: Opportunities and Future Perspective toward Sustainable Nation. *Process Saf. Environ. Prot.* **2024**, *185*, 392–407. [CrossRef]

14. Hewitt, J.; Holden, M.; Robinson, B.L.; Jewitt, S.; Clifford, M.J. Not Quite Cooking on Gas: Understanding Biogas Plant Failure and Abandonment in Northern Tanzania. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112600. [CrossRef]
15. Robinson, B.L.; Clifford, M.J.; Jewitt, S. TIME to Change: Rethinking Humanitarian Energy Access. *Energy Res. Soc. Sci.* **2022**, *86*, 102453. [CrossRef]
16. IEA. Uganda—Countries & Regions. Available online: https://www.iea.org/countries/uganda (accessed on 6 September 2024).
17. ABPP. Evaluation of ABPP: Executive Summary. 2019.
18. SNV. Africa Biogas Component Project. Available online: https://snv.org/update/addressing-gaps-enabling-environment-small-and-medium-scale-biodigesters-kenya (accessed on 6 February 2023).
19. Mukisa, P.J.; Ketuama, C.T.; Roubík, H. Biogas in Uganda and the Sustainable Development Goals: A Comparative Cross-Sectional Fuel Analysis of Biogas and Firewood. *Agriculture* **2022**, *12*, 1482. [CrossRef]
20. Ullrich, E.G.; Radtke, E.R.; Chepkwony, S.; Mwenja, K. *Biogas Construction Manual: Theory Training on Biogas Plant Construction*; GIZ Gmbh: Nairobi, Kenya, 2011.
21. Lwiza, F.; Mugisha, J.; Walekhwa, P.N.; Smith, J.; Balana, B. Dis-Adoption of Household Biogas Technologies in Central Uganda. *Energy Sustain. Dev.* **2017**, *37*, 124–132. [CrossRef]
22. Price, R. *"Clean" Cooking Energy in Uganda—Technologies, Impacts, and Key Barriers and Enablers to Market Acceleration*; Institute of Development Studies: Brighton, UK, 2017.
23. GIZ. *Sector Brief Uganda: Renewable Energy*; Business Scouts for Development; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Eschborn, Germany, 2022.
24. Ministry of Energy and Mineral Development. *The Energy Policy*; Ministry of Energy and Mineral Development: Kampala, The Republic of Uganda, 2002.
25. Ministry of Energy and Mineral Development. *Renewable Energy Policy*; Ministry of Energy and Mineral Development: Kampala, The Republic of Uganda, 2007.
26. Government of Uganda. *Uganda Vision 2040*; Government of Uganda: Kampala, The Republic of Uganda, 2012.
27. Mweninguwe, R. Biogas Innovation: Clean Energy and Fertiliser for Malawi's Farmers. Development and Cooperation. 2024. Available online: https://www.dandc.eu/en/article/ecogen-malawian-start-transforms-animal-waste-biogas-and-bio-fertiliser-providing-farmers (accessed on 16 December 2024).
28. ESMAP Malawi—Tracking SDG 7. Available online: https://trackingsdg7.esmap.org/country/malawi (accessed on 16 December 2024).
29. MECS; ESMAP. AFREC. *Sustainable Scaling: Meeting the Clean Cooking Challenge in Africa*. 2024. Available online: https://au-afrec.org/sustainable-scaling-meeting-clean-cooking-challenge-africa (accessed on 10 December 2024).
30. ESMAP. *Malawi CCDR: Clean Cooking Sector Background Note*; World Bank: Washington DC, USA, 2022.
31. Kapadia, K. *Productive Uses of Renewable Energy: A Review of Four Bank-GEF Projects*; World Bank: Washington, DC, USA, 2004; pp. 1–33.
32. Terrapon-Pfaff, J.; Gröne, M.-C.; Dienst, C.; Ortiz, W. Productive Use of Energy—Pathway to Development? Reviewing the Outcomes and Impacts of Small-Scale Energy Projects in the Global South. *Renew. Sustain. Energy Rev.* **2018**, *96*, 198–209. [CrossRef]
33. Cleary, K.; Palmer, K. *Energy-as-a-Service: A Business Model for Expanding Deployment of Low-Carbon Technologies*; Resources for the Future: Washington, DC, USA, 2019.
34. IRENA. *Energy as a Service: Innovation Landscape Brief*; IRENA: Masdar City, Abu Dhabi, 2020.
35. Shupler, M.; Karl, J.; O'Keefe, M.; Hoka Osiolo, H.; Perros, T.; Nabukwangwa Simiyu, W.; Gohole, A.; Lorenzetti, F.; Puzzolo, E.; Mwitari, J.; et al. Gendered Financial & Nutritional Benefits from Access to Pay-as-You-Go LPG for Cooking in an Informal Settlement in Nairobi, Kenya. *World Dev. Sustain.* **2024**, *5*, 100178. [CrossRef]
36. Wahlund, M.; Palm, J. The Role of Energy Democracy and Energy Citizenship for Participatory Energy Transitions: A Comprehensive Review. *Energy Res. Soc. Sci.* **2022**, *87*, 102482. [CrossRef]
37. EnDeva. *G20 Inclusive Business Framework*; EnDeva: Pyrmont, Australia, 2024.
38. Grimsby, L.K.; Ulsrud, K.; Vindegg, M.; Ruhinduka, R.D.; Puzzolo, E.; Pope, D.; Rubinstein, F.; Standal, K.; Aamaas, B. New Perspectives on Multiple Fuel Use: Energy Flexibility in Household Cooking Solutions in Tanzania. *Energy Res. Soc. Sci.* **2024**, *115*, 103636. [CrossRef]
39. Bray, R.; Ford, R.; Morris, M.; Hardy, J.; Gooding, L. The Co-Benefits and Risks of Smart Local Energy Systems: A Systematic Review. *Energy Res. Soc. Sci.* **2024**, *115*, 103608. [CrossRef]
40. Gill-Wiehl, A.; Kammen, D.M.; Haya, B.K. Pervasive Over-Crediting from Cookstove Offset Methodologies. *Nat. Sustain.* **2024**, *7*, 191–202. [CrossRef]
41. Simon, J. On Today's Release from C-Quest Capital Regarding Allegations Against Former C-Quest CEO Ken Newcombe. Available online: https://verra.org/c-quest-capital-statement/ (accessed on 10 September 2024).

42. Leach, M.; Bricknell, M. *The Importance of Metered Methodologies for Carbon Credit Certification of Modern Energy Cooking Projects—Modern Energy Cooking Services*; Modern Energy Cooking Services Programme; Loughborough University: Loughborough, UK, 2024.
43. Gold Standard. *Methodology for Metered & Measured Energy Cooking Devices*; Gold Standard for the Global Goals: Geneva, Switzerland, 2022.
44. Gold Standard. *Methodology for Animal Manure Management and Biogas Use for Thermal Energy Generation*; Gold Standard for the Global Goals: Geneva, Switzerland, 2023.
45. Gold Standard. Kenya Biogas Programme. Available online: https://marketplace.goldstandard.org/products/kenya-biogas-programme (accessed on 11 September 2024).
46. SNV. Unlocking Climate Finance to Promote the Use of Biodigesters Through Digital Innovation. Available online: https://www.snv.org/update/unlocking-climate-finance-to-promote-the-use-of-biodigesters-through-digital-innovation (accessed on 11 September 2024).
47. Robinson, B.L.; Clifford, M.J.; Jewitt, S. Transforming North-South Research Partnerships: Lessons Learned from Energy, Technology & Enterprise Global Challenge Research Fund Projects. *Energy Res. Soc. Sci.* **2022**, *93*, 102837. [CrossRef]
48. Inclusive Energy. *Who's Counting? Exploring Whether Data Pays in Biogas Carbon Projects*; Inclusive Energy: London, UK, 2023.
49. Batchelor, S. ATEC & MECS to Pilot Digitised 'Cook to Earn'. Available online: https://mecs.org.uk/blog/atec-mecs-to-pilot-digitised-cook-to-earn/ (accessed on 5 March 2024).
50. Shah, K.; Berman, A.; Kimani, C.; Shamakamba, C. *Unlocking Local Value: Rethinking Benefit Sharing in African Carbon Projects*; Climate Action Platform Africa: Nairobi, Kenya, 2024.
51. Little, M.; Richter, A.; Eales, A.; Müller-Karpe, Z. *A Review of the Standards, Methodologies, Technical Needs and Available Resources Related to Digital Monitoring, Reporting and Verification for Modern Cooking Devices in the Context of Carbon Finance*; Modern Energy Cooking Services Programme; Loughborough University: Loughborough, UK, 2023.
52. ixo Home—The Internet of Impacts. Available online: https://www.ixo.world/ (accessed on 11 September 2024).
53. Bisaga, I.; Campbell, K. *Clean and Modern Energy for Cooking: A Path to Food Security and Sustainable Development*; WFP: Roma, Italy, 2022.
54. Robinson, B.L.; Clifford, M.J.; Hewitt, J.; Jewitt, S. Cooking for Communities, Children and Cows: Lessons Learned from Institutional Cookstoves in Nepal. *Energy Sustain. Dev.* **2022**, *66*, 1–11. [CrossRef]
55. Kemausuor, F.; Adaramola, M.S.; Morken, J. A Review of Commercial Biogas Systems and Lessons for Africa. *Energies* **2018**, *11*, 2984. [CrossRef]
56. Practical Action PMSD Toolkit. Available online: https://practicalaction.org/pmsd-toolkit/ (accessed on 4 May 2023).
57. EnDev. *Humanitarian Energy: Energy for Micro-Enterprises in Displacement Settings*; EnDeva: Pyrmont, Austrralia, 2021.
58. Shuma, J.C.; Sawe, E.; Clements, A.; Meena, S.B.; Aloyce, K.; Ngaya, A.E. eCooking Delivery Models: Approach to Designing Delivery Models for Electric Pressure Cookers with Case Study for Tanzania. *Energies* **2022**, *15*, 771. [CrossRef]
59. Garside, B.; Wykes, S. *Planning Pro-Poor Energy Services for Maximum Impact: The Energy Delivery Model Toolkit*; IIED: London, UK, 2017.
60. Osterwalder, A.; Pigneur, Y. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*, 1st ed.; Wiley John + Sons: Hoboken, NJ, USA, 2010; ISBN 978-0-470-87641-1.
61. Wilson, E.; Wood, R.G.; Garside, B. *Sustainable Energy for All? Linking Poor Communities to Modern Energy Services*; IIED: London, UK, 2012.
62. The Independent Museveni Bans Charcoal Trade, Balaalo Herdsmen from Northern Uganda. *The Independent Uganda*. 2023. Available online: https://www.independent.co.ug/museveni-bans-charcoal-trade-balaalo-herdsmen-from-northern-uganda/ (accessed on 10 December 2024).
63. World Bank. Development Projects: Electricity Access Scale-Up Project (EASP)—P166685. Available online: https://projects.worldbank.org/en/projects-operations/project-detail/P166685 (accessed on 19 September 2024).
64. UECCC. *Biogas Loan Programme*; UECCC: Kampala, The Republic of Uganda, 2021.
65. The Independent Equity Bank Uganda Launches Equi-Green Loan Financing for Renewable Clean Technologies. *The Independent Uganda*. 2022. Available online: https://www.independent.co.ug/equity-bank-uganda-launches-equi-green-loan-financing-for-renewable-clean-technologies/ (accessed on 19 September 2024).
66. Government of Malawi. *National Energy Policy*; Government of M alawi: Lilongwe, Malawi, 2018.
67. Namugenyi, I.; Scholderer, J. Valorisation of Biogas for Market Development and Remission of Environmental Nuisance in Uganda. *Clean. Energy Syst.* **2024**, *8*, 100116. [CrossRef]
68. National Agricultural Research Organisation NARO. About—National Agricultural Research Organisation (NARO). Available online: https://naro.go.ug/about-us/naro-about-us/ (accessed on 17 December 2024).
69. Ireri, B.; Kilonzo Jnr, M.K.J. A New Solution to Power Africa: Productive Use of Renewable Energy 2024. Available online: https://www.wri.org/insights/productive-use-renewable-energy-africa (accessed on 10 December 2024).

70. ESMAP. *Accelerating the Productive Use of Electricity: Enabling Energy Access to Power Rural Economic Growth*; World Bank: Washington, DC, USA, 2023.
71. EnDev. *Productive Use of Energy*; EnDeva: Pyrmont, Austrralia, 2024.
72. Global Energy Alliance for People and Planet Productive Use of Energy | What We Do. Available online: https://energyalliance.org/productive-use-energy/ (accessed on 3 December 2024).
73. Robinson, B.L.; Clifford, M.J.; Ouma, E.O.; Kinyangi, K.K.; Adimo, M.W.; Muchoki, C.N.; Gathogo, G.; Kithinji, L.K.; Ngigi, T.W.; Mbuguah, T.N.; et al. Stepping on the Gas: Pathways to Reduce Venting in Household-Scale Kenyan Biogas Digesters. *Energy Res. Soc. Sci.* **2025**, *121*, 103963. [CrossRef]
74. Puzzolo, E.; Pope, D.; Stanistreet, D.; Rehfuess, E.; Bruce, N. Clean Fuels for Resource-Poor Settings: A Systematic Review of Barriers and Enablers to Adoption and Sustained Use. *Environ. Res.* **2016**, *146*, 218–234. [CrossRef] [PubMed]
75. Nevzorova, T.; Kutcherov, V. Barriers to the Wider Implementation of Biogas as a Source of Energy: A State-of-the-Art Review. *Energy Strategy Rev.* **2019**, *26*, 100414. [CrossRef]
76. Systema Bio Product Catalogue—Kenya. 2024.
77. Wang, X.; Lo, K. Just Transition: A Conceptual Review. *Energy Res. Soc. Sci.* **2021**, *82*, 102291. [CrossRef]
78. Elrha. *The Role of Community-Led Innovation in Decolonising Aid*; Elrha: Cardiff, UK, 2021.
79. Mitova, V. Decolonising Knowledge Here and Now. *Philos. Pap.* **2020**, *49*, 191–212. [CrossRef]
80. Groenewoudt, A.C.; Romijn, H.A. Limits of the Corporate-Led Market Approach to off-Grid Energy Access: A Review. *Environ. Innov. Soc. Transit.* **2022**, *42*, 27–43. [CrossRef]
81. Hamid, R.G.; Blanchard, R.E. An Assessment of Biogas as a Domestic Energy Source in Rural Kenya: Developing a Sustainable Business Model. *Renew. Energy* **2018**, *121*, 368–376. [CrossRef]
82. EEP. *Clean Energy and Fertilizer*; SIMGAS: Zuid-Holland, The Netherlands, 2019.
83. Ministry of Petroleum and Natural Gas. *Sustainable Alternative Towards Affordable Transportation*; Government of India: New Delhi, India, 2018.
84. Grassroots Energy Small Scale Innovations Large Scale Impact. Available online: https://www.grassrootsenergy.co (accessed on 12 December 2024).
85. Dutt, D. Mediators of Change: Intermediaries in India's Compressed Biogas Niche. *Energy Res. Soc. Sci.* **2024**, *117*, 103716. [CrossRef]