CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Tropical AgriSciences

Understanding the viability and sustainable transition pathways of small-scale biogas technology in rural areas of Cameroon

DISSERTATION THESIS

Student: Chama Theodore Ketuama, MEng, MSc.

Department: Department of Sustainable Technologies

Supervisor: doc. Ing. Hynek Roubík, PhD

Co-supervisor: Ing. Jana Mazancová, PhD

Prague, February 2025

Declaration

I hereby affirm that I have done this thesis entitled "**Understanding the viability and sustainable transition pathways of small-scale biogas technology in rural areas of Cameroon**" independently except for jointly authored publications that are included. In the case of such publications, my specific contributions to each chapter have been clearly stated at their respective beginnings. Furthermore, I affirm that proper acknowledgement has been provided within this thesis for any references made to the works of others, I also ensure that this work has not been and is not being submitted for any other degree to this or any other university. All the sources have been quoted and acknowledged by means of complete references and according to citation rules of the FTA.

In Prague, February 6th, 2025.

Chama Theodore Ketuama

Acknowledgements

I am deeply grateful to my supervisor, Assoc. Prof. Ing. Hynek Roubík, PhD for his academic, financial and emotional support throughout my doctoral studies. Through him and Ing. Jana Mazancová, PhD, I gained not only research but more practical skills in rural development project identification, planning and implementation.
I am grateful for the financial support I received from the Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague. This research was supported by the Internal Grant Agency, Grant Nos [20223111, 20233111 and 20243111]. The mobility in 2023 was funded by the Erasmus+ Credit Mobility KA107.
I would like to thank Cameroon's Minister of Agriculture and Rural Development, His Excellency Gabriel Mbaïrobe, for permitting me to undertake my doctoral studies. I am very grateful to Prof. Tangka Julius Kewir and Assoc. Prof. Balgah Roland Azibo for their unwavering support and mentorship, accompanying me from my undergraduate to doctoral studies.
I would like to thank all the members of the BioResources and Technology Division, the Department of Sustainable Technologies and all my friends for their support throughout my doctoral studies.
Finally, I greatly appreciate the emotional support my family provided me during these challenging years of my doctoral studies.

Abstract

Since the first government initiative in 1979 to promote small-scale biogas technology in Cameroon, less than 1% of the available biogas potential has been realized. This study applies multiple research methods to analyze the causes of the slow uptake of biogas technology as an alternative source of energy and ways of sustaining its production and use in rural areas of Cameroon. Results show that the most dominant constraint hindering the development of small-scale biogas technology in SSA countries, including Cameroon, is economic (lack of funding). In decreasing order of significance, the other constraints are political, social, technical, legal and environmental.

Economically, the studied biogas plants are viable. Benefit-cost ratios were 1.01, 1.19, 1.50, 1.02, 1.21 and 2.04 for the $4m^3$, $6m^3$, $8m^3$, $10m^3$, $20m^3$, and $25m^3$ biogas plants. The net present values in US dollars (USD) were 959, 1790, 2695, 2658, 6047, and 12267 for the $4m^3$, $6m^3$, $8m^3$, $10m^3$, $20m^3$, and $25m^3$ biogas plants respectively. The internal rates of return were higher than the applied discount rate of 12%. The minimum payback period of 2.24 years was recorded for the $25m^3$ while the maximum of 3.37 years was recorded for the $10m^3$ biogas plants respectively. The mean willingness to pay is estimated at 13 USD or 8000 FCFA. This resulted in an average repayment period of 11.5 years.

The impact assessment of small-scale biogas technology in rural areas of Cameroon shows positive results on the beneficiaries' livelihood assets. The dominant impact of biogas technology was financial, as the beneficiaries witnessed a significant increase in their household incomes. This was

possible through the reduction of the expenditure on fuelwood and the sale of digestate.
In relation to the factors influencing the choice of biogas plants in rural areas of Cameroon, household income and opportunities are the most significant in rural areas of Cameroon. Three pathways to sustain biogas technology have been identified, including the productive use of biogas, cost-sharing to reduce the financial burden and a pathway that empowers the vulnerable population to obtain and sustain their biogas plants.
The Cameroon's biogas innovation system is still weak but emergent. This is caused by combined systemic problems resulting from a poor institutional setting, lack of legitimacy, weak biogas actor-network, inadequate funding and technical capacity to sustain the technology. Building a resilient biogas market in Cameroon requires providing solutions to the current systemic problems.

Keywords: Biogas; economic viability; willingness to pay; clean cooking; behaviour change; energy transition; bioenergy policy; Cameroon.

Résumé

Depuis la première initiative gouvernementale en 1979 visant à promouvoir la technologie du biogaz à petite échelle au Cameroun, moins de 1% du potentiel disponible en biogaz a été exploité. Cette étude applique plusieurs méthodes de recherche pour analyser les causes de la faible adoption de la technologie du biogaz comme source d'énergie alternative et les moyens de rendre durable la production et l'utilisation dans les zones rurales du Cameroun. Les résultats montrent que la contrainte la plus dominante qui entravent le développement de la technologie du biogaz à petite échelle dans les pays d'Afrique subsaharienne, y compris le Cameroun, est économique (manque de financement). Dans l'ordre décroissant de leur importance, les autres contraintes sont politiques, sociales, techniques, juridiques et environnementales.

Sur le plan économique, les biodigesteurs étudiées sont viables. Les rapports bénéfices-coûts étaient de 1,01, 1,19, 1,50, 1,02, 1,21 et 2,04 pour les biodigesteurs de $4m^3$, $6m^3$, $8m^3$, $10m^3$, $20m^3$ et $25m^3$ respectivement. Les valeurs présentes nettes en dollars américains (USD) étaient de 959, 1790, 2695, 2658, 6047 et 12267 pour les biodigesteurs de $4m^3$, $6m^3$, $8m^3$, $10m^3$, $20m^3$ et $25m^3$ respectivement. Les taux de rendement internes étaient supérieurs au taux d'actualisation appliqué de 12%. La période de récupération minimale de 2,24 ans a été enregistrée pour le $25m^3$, tandis que la maximale de 3,37 ans a été enregistrée pour les biodigesteurs de $10m^3$ respectivement. La moyenne de la volonté de payer est estimée à 13USD ou 8000 FCFA. Cela a entraîné une période de remboursement moyenne de 11,5 ans.

L'évaluation de l'impact de la technologie du biogaz à petite échelle dans les zones rurales du Cameroun montre des résultats positifs sur les moyens de subsistance des bénéficiaires. L'impact dominant de la technologie du biogaz a été financier, les bénéficiaires ayant constaté une augmentation significative de leurs revenus ménagers. Cela a été possible grâce à la réduction des dépenses en bois de chauffage et à la vente de digestat.
En ce qui concerne les facteurs qui influencent le choix des biodigesteurs dans les zones rurales du Cameroun, le revenu et les opportunités disponibles aux ménages sont les plus importants. Trois voies ont été identifiées pour pérenniser la technologie du biogaz, notamment l'utilisation productive du biogaz, le partage des coûts pour réduire la charge financière et une voie qui permet aux populations vulnérables d'obtenir et de pérenniser leurs systèmes à biogaz.
Le système d'innovation de biogaz du Cameroun est encore faible mais émergent. Cela est dû à des problèmes systémiques connexes résultant d'un environnement institutionnel imparfait, d'un manque de légitimité, d'un réseau d'acteurs du biogaz faible, d'un financement insuffisant et d'une capacité technique insuffisante pour soutenir la technologie. La création d'un marché du biogaz résilient au Cameroun nécessite de trouver des solutions aux problèmes systémiques actuels.

Mots clés : Biogaz; rentabilité économique; volonté de payer; cuisson propre; changement de comportement; transition énergétique; politique bioénergétique; Cameroun.

Abstrakt

Od první vládní iniciativy v roce 1979 na podporu technologie bioplynu v malém měřítku v Kamerunu bylo realizováno méně než 1 % dostupného potenciálu bioplynu. Tato studie využívá více výzkumných metod k analýze příčin pomalého zavádění technologie bioplynu jako alternativního zdroje energie a způsobů, jak zajistit udržitelnou výrobu a využití ve venkovských oblastech Kamerunu.. Výsledky ukazují, že omezením bránícím rozvoji malých bioplynových stanic v zemích subsaharské Afriky, včetně Kamerunu, je především ekonomická (nedostatek finančních prostředků). V klesajícím pořadí významnosti jsou dalšími omezeními politická, sociální, technická, právní a environmentální.

Bioplynové stanice podrobené studii jsou ekonomicky životaschopné. Poměr nákladů a přínosů byl 1,01, 1,19, 1,50, 1,02, 1,21 a 2,04 pro bioplynové stanice o objemu 4 m^3, 6 m^3, 8 m^3, 10 m^3, 20 m^3 a 25 m^3. Čisté současné hodnoty v amerických dolarech (USD) byly 959, 1790, 2695, 2658, 6047 a 12267 pro bioplynové elektrárny 4 m^3, 6 m^3, 8 m^3, 10 m^3, 20 m^3 a 25 m^3. Vnitřní míry návratnosti byly vyšší než aplikovaná diskontní sazba 12%. Minimální doba návratnosti 2,24 roku byla zaznamenána pro 25 m^3, zatímco maximální 3,37 roku byla zaznamenána pro bioplynové elektrárny 10 m3. Průměrná ochota platit je odhadována na 13 USD nebo 8000 FCFA. To vedlo k průměrné době splácení 11,5 let.

Hodnocení dopadu technologie malých bioplynových stanic ve venkovských oblastech Kamerunu ukazuje na pozitivní výsledky na živobytí příjemců. Dopad implementace technologie byl především ekonomický, neboť příjemci zaznamenali výrazný nárůst svých příjmů domácnosti. To bylo

možné díky snížení výdajů na palivové dřevo a prodeji digestátu.
Pokud jde o faktory ovlivňující rozhodnutí zavádění bioplynových stanic ve venkovských oblastech Kamerunu, příjem domácnost a příležitosti jsou ve venkovských oblastech Kamerunu nejvýznamnější. Byly identifikovány tři cesty za cílem udržení technologie bioplynu, včetně efektivního využití bioplynu, sdílení nákladů ke snížení finanční zátěže a způsobům, jak umožnit ekonomicky zranitelným skupinám obyvatel získat a provozovat si své bioplynové stanice.
Proces inovace bioplynových stanic v Kamerunu je stále nedostatečný, avšak rozvíjející se. Je to způsobeno kombinovanými systémovými problémy vyplývajícími ze špatného institucionálního prostředí, nedostatku legitimity, slabé sítě aktérů v oblasti bioplynu, nedostatečného financování a technické kapacity k udržení technologie. Vytvoření robustního trhu s bioplynem v Kamerunu vyžaduje úspěšné řešení současných systémových problémů.

Klíčová slova: Bioplyn, ekonomická životaschopnost, ochota platit, čisté vaření, změna chování, energetická transformace, bioenergetická politika, Kamerun.

Table of contents

List of tables

Chapter 5.

Chapter 6.

List of figures

Abbreviations

ABPP	Africa Biogas Partnership Programme
CDM	Clean Development Mechanism
GHG	Greenhouse gas
GIZ	German Development Cooperation
HAP	Household air pollution
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MFI	Micro-finance Institution
MINADER	Ministry of Agriculture and Rural Development
MINEE	Minister of Water and Energy Resources
MINEPIA	Ministry of Livestock, Fisheries and Animal Husbandry
MVP	Multivariate Probit
NBP	National Biogas Programme
PESTLE	Political, economic, social, technological, legal, environmental
RET	Renewable Energy Technology
SDG	Sustainable Development Goal
SE4ALL	Sustainable Energy for All
SNV	The Netherlands Development Organization
SSA	sub-Saharan Africa
UNDP	United Nations Development Programme
WBA	World Biogas Association
WTP_i	Farmer *i*'s unobservable true willingness to pay
WTP_m	Mean willingness to pay

1. Introduction

1.1. Background of the study

The current global energy transition is fundamentally shifting away from fossil fuels (e.g. coal, crude oil, and natural gas) towards cleaner, renewable energy sources (e.g. solar, wind power, bioenergy and hydroelectricity, including tidal energy). Bioenergy, such as biogas, is promoted in rural areas of developing countries as a means to generate income, reduce oil dependency and meet the rising clean energy needs of economic growth (Sulle & Nelson 2009; Hepher 2010). In 2022, approximately 685 million people worldwide still lacked access to electricity, while 2.1 million still depended on polluting energy sources for cooking (IEA et al. 2024). Most of this population is residing in Sub-Saharan Africa (SSA). In Cameroon, for example, only 65.4% of the population had access to electricity in 2022 (IEA et al. 2024). Access to electricity was higher in urban areas, reaching up to 94.7%. In rural areas, only 24.8% of the population had access to electricity, and only 26% had access to clean energy. In Cameroon, like other developing countries, the lower access to clean energy in rural areas is partly caused by the difficulty in extending expensive infrastructure to geographically isolated areas. Other factors such as low population density, limited economic activities, and insufficient government funding, have contributed to low access to energy (World Bank 2018).

Since the first government initiative in 1979 to promote small-scale biogas technology in Cameroon, less than 1000 small-scale biogas plants have been constructed in the country. This represents less than 1% of the available biogas potential. Consequently, in rural areas of Cameroon, over-reliance on traditional energy sources such as firewood and charcoal continue to contribute to health issues and environmental degradation through household air pollution (HAP), deforestation and greenhouse gas (GHG) emissions. Small-scale biogas technology (BGT) offers a promising alternative to traditional fuels by converting organic waste into clean energy, improving rural livelihoods through waste management and producing bio-slurry as fertilizer. According to MINEE (2010), promoting biogas technology in Cameroon can reduce poverty and enable access to modern energy for rural and vulnerable populations.

Lessons learnt from different countries in the world reveal that small-scale biogas succeeded more in Asian countries such as China, Nepal, Vietnam and Bangladesh than in African countries (Mukeshimana et al. 2021). Cameroon still lags behind many African countries where National Biogas Programmes have been implemented. The built capacity of small-scale biogas plants in Kenya is approximately 20,000 (MEP 2023), 10,000 in Ethiopia (Kefalewet al. 2021), 12,000 in Tanzania (Hewitt et al. 2022) and 2700 in Rwanda (Mukeshimana et al. 2021) respectively. Less than 1000 biogas plants have been reported in Cameroon (Ndongsok et al. 2018; Ketuama & Roubik 2024). The main barriers to the development of biogas technology in these countries have been reportedly related to the high investment costs, inadequate institutional support, lack of public awareness, and poor technical skills for maintaining biogas plants. The failure to address these barriers has resulted in the underutilization of biogas, which could otherwise play a crucial role in addressing energy poverty and achieving sustainable development goals (SDGs), particularly SDG 7 on clean energy access. Biogas systems can also contribute to achieving 11 other SDGs

(Obaideen et al. 2022; Mukisa et al. 2022), thereby having the potential to play a major role in the sustainable development of the areas in which they are implemented.

1.2. Objectives of the study

1.2.1. Main objective

Despite its high renewable energy potential, Cameroon, like many Sub-Saharan Africa (SSA) countries, struggles to provide sustainable energy solutions to its rural population. The development of small-scale biogas technology in rural areas necessitates its economic, environmental, social, and to some extent, spiritual sustainability (Fulford 2015). Biogas plants can produce economic, social, and environmental co-benefits (World Bank 2018). The duration of use of biogas technology in part depends on the level of achievement of the latter benefits. Otherwise, it will fail. Addressing sustainability issues contributes to achieving long-term use of the technology. In contribution to understanding these issues, this study mainly aims to understand the economic viability and pathways of sustaining small-scale biogas technology in rural areas of Cameroon.

1.2.2. Specific objectives

The specific objectives include:

- Identifying the major barriers to small-scale biogas technology development in sub-Saharan Africa.
- Evaluating the economic viability of small-scale biogas plants in Cameroon through cost-benefit analysis.

- Investigating the factors influencing rural farmers' willingness to pay for small-scale biogas plants using contingent valuation and probit regression model.
- Assessing the socio-economic and environmental impacts of small-scale biogas technology on rural households in Cameroon using the Sustainable Livelihoods Framework.
- Analysing the factors influencing households' choice of small-scale biogas plant size in Cameroon using the multivariate probit model.
- Identifying pathways of uptake of small-scale biogas technology in rural areas of Cameroon.
- Exploring the causes of the slow transition to small-scale biogas technology in rural Cameroon using the technological innovations systems approach.

1.3. Relevance of this study

The study contributes to the global debate on renewable energy and sustainable development, aligning with SDG 7 (Clean and Affordable Energy), Cameroon's 2030 National Development Strategy (NDS), Cameroon's Vision 2035, and the African Union's Agenda 2063. This research provides empirical evidence on the economic viability, other socio-economic benefits, pathways for sustainability and changes needed to develop a functional biogas innovation system to promote small-scale biogas technology in rural areas of Cameroon. This study contributes to both the academic literature and practical policy discussions on small-scale biogas technology development in Cameroon. Insights from the study are expected to inform policy interventions aimed at promoting biogas as a viable and sustainable energy source, thereby contributing to Cameroon's energy transition goals and broader global energy sustainability targets.

1.4. Structure of the thesis and methods used

The thesis is divided into six main chapters as follows:
Chapter 1 is an introduction to this thesis.

Chapter 2 provides an overview of small-scale biogas technology in SSA with the goal of identifying the barriers to its development. The methods used comprised the PRISMA approach for literature review and the PESTLE framework for identifying the constraints. The severity of the constraints was assessed using a weighting approach based on the reporting frequency in the papers studied.

Chapter 3 focuses on the economic viability of small-scale biogas technology and factors affecting farmers' willingness to pay for it. Economic viability was determined by estimating the benefit-cost ratio for each biogas plant, which was complemented by other determinants such as the net present value, payback period, and sensitivity analysis. The willingness to pay for $8m^3$ (biogas plant size meeting energy needs – for cooking of most rural households) was estimated using contingent valuation. The factors influencing farmers' willingness to pay for their domestic biogas plants were assessed using the probit regression model.

Chapter 4 is a continuation of the analysis of the socio-economic aspects of the rural biogas plants being used by the rural dwellers. This consisted mainly of an assessment of the impact of biogas technology on rural users and the environment. The Sustainable Livelihoods Framework was used.

Chapter 5 examines the factors influencing the choice of biogas plant size among rural households. The multivariate probit model was used, based on the COM-B model of behaviour to assess the factors influencing the adoption of the different sizes of biogas plants in rural Cameroon. Furthermore, pathways to adopting and sustaining biogas technology in rural areas of Cameroon were identified.

Chapter 6 explores the systemic problems causing the slow transition to small-scale biogas technology in rural areas of Cameroon. The technological innovation systems (TIS) framework was used for the analysis. This chapter identifies the gaps from the rural small-scale biogas case study in developing a national biogas innovation system and provides policy recommendations for its improvement.

2. Overview and barriers of small-scale biogas technology development in sub-Saharan Africa

Adapted from Ketuama CT, Mazancová J. Roubík H. 2022. Impact of market constraints on the development of small-scale biogas technology in sub-Saharan Africa: a systematic review. Environmental Science and Pollution Research, 29, 65978–65992. doi: 10.1007/s11356-022-22262-y.

Contributions: All authors conceived the idea for the paper. Chama Theodore Ketuama identified relevant literature, analysed the data and wrote the original manuscript. Revisions were done by Chama Theodore Ketuama, Jana Mazancová, and Hynek Roubík. Supervision was done by Hynek Roubík.

Abstract

The sustainable production and use of small-scale biogas energy is needed to ensure clean household energy access in developing countries, including the sub-Saharan Africa (SSA) region. This is influenced by market risks which can be identified as political, economic, social, technical, legal and environmental (PESTLE). This study examines peer-reviewed and grey literature for the period from 2000 to 2020 to identify the PESTLE constraints and assess their impact on the sustainable deployment of the technology in the SSA region. The production of biogas with small-scale plants is commonly done by rural and peri-urban households. Results show that economic constraints are the most dominant and reducing at a slow pace. This is followed by political constraints, which have received much attention in the last two decades. Despite the provided policy improvements, national bioenergy policies and interventions are still to make significant gains, especially in

the Central African region. In order of significance, the Southern, East and West Africa regions have made comparably greater progress in reducing the constraints. To achieve sustainable development of the technology, there is a need to further address the PESTLE constraints at national and regional levels. This study partly deduces that the unsustainable production, use and inadequate regulation of the small-scale biogas sector is delaying its transition in the SSA region.

Keywords: Biogas, energy access, bioenergy policy, developing countries, Africa

2.1. Introduction

Biogas technology is considered a cost-effective method of reducing greenhouse gas (GHG) emissions from biomass or organic wastes, reducing deforestation and household air pollution and improving rural sanitation through appropriate waste management. Biogas is clean energy produced after anaerobic digestion or fermentation of various biomass materials (IRENA 2017). As the world is mobilising for a transition to clean energy, it is essential to understand changes in the political, economic, social, technological, environmental and legal (PESTLE) factors affecting the development of small-scale biogas technology (BGT) in sub-Saharan Africa (SSA). Since the introduction of biogas technology in Africa after World War II, small-scale biogas development still needs to be researched (Parawira 2009). Between 1980 and 2000, only about 2400 biogas units were installed in sub-Saharan Africa through donor and demonstration projects (Martinot et al. 2002). Karekezi et al. (2003) stated that the success of renewable energy technologies (RETs) in the SSA region was limited by a combination of factors which are institutional and infrastructural in nature; inadequate RET planning policies; lack of coordination and linkage in the RET programme; pricing distortions which are not advantageous to renewable energy; high capital investment costs; weak dissemination strategies; insufficient qualified manpower; insufficient baseline information; and, weak maintenance service and infrastructure. The current situation has evolved and will greatly impact the attainment of the sustainable development goals and the Agenda 2063 of the African Union, which aims by 2063 to develop efficient, reliable, affordable and environmentally friendly energy networks through the development of clean power generation and development of renewable energy resources (including biogas).

The Millennium Development Goals (MDGs) were among the initiatives established in 2000 to fight poverty in its many dimensions for 15 years. Biogas technology development was addressed by mainly MDG 7 Ensure environmental sustainability) (United Nations 2015). In 2013, the United Nations initiated the Sustainable Energy for All (SE4ALL) initiative in connection with the 2030 Agenda for Sustainable Development. Specifically, the Sustainable Development Goal (SDG) 7 emphasises the imperatives of achieving universal access to energy through increases in access to renewable or clean energy and improved energy efficiency (UNDP 2018). Three main approaches have been commonly used to deploy biogas technology in developing countries. These include the holistic, life cycle and the market-oriented approaches. The holistic approach focuses on the acceptability and performance of the biogas plant. The emphasis of this approach is laid on the adjustment of the existing processes for the management of solid waste, improvement in the usage of biogas and manure and the addition of competing technologies. The life cycle approach aims to assess the practicability of biogas projects to understand the critical feasibility components of the biogas interventions. Finally, the market-oriented approach focuses on the different stakeholders that are involved at the different levels of the value chain of the biogas project implementation. This approach has much been used by the fore promoters of biogas technology in the region including the Netherlands Development Organization (SNV), International Humanist Institute for Cooperation with Developing Countries (Hivos), German Technical Cooperation (GIZ) and Heifer International. Therefore, a market analysis of the outcomes of these biogas technology interventions is necessary to learn past lessons and provide perspectives for future development.

Evidence from SSA shows that biogas plants have contributed to improving the livelihoods of rural households through demonstrated positive impacts on the social, financial, human and physical capital (Balgah et al. 2018). The increasing wood resource scarcity makes the market price of firewood and charcoal more expensive, which keeps households in poverty (IRENA 2018). Conversely, biogas technology lowers energy and fuel costs, reducing poverty (Rahman et al. 2021). In a comparison of firewood and biogas, Buysman (2015) showed that biogas technology reduced particulate matter concentration and carbon monoxide (CO), resulting in improved indoor air quality. The residues of anaerobic digestion (digestate) have been used as organic fertiliser and biopesticide to improve food production (Valentinuzzi et al. 2020). The use of biogas technology to treat domestic wastewater, organic waste, brown water, blackwater, and excreta has improved sanitation in households (Mang & Li 2010). Biogas technology can reduce the exploitation of trees for firewood (Parawira 2009) and contribute to carbon sequestration in soils, soil erosion, degradation and reduced deforestation (Al 2011).

SSA makes up 14.65% (December 2020) of the world's population. However, SSA has the lowest energy access rates in the world. In 2019, access to electricity in SSA was 48%; meanwhile, clean cooking was lagging at 15%. This implies that up to 85% of the population still relied on inefficient, polluting and traditional cooking systems. Regarding small-scale biogas plants, the total number in 2012 had risen to nearly 23,000. By December 2018, the number rose to 75,561 with the involvement of other agencies under the Africa Biogas Partnership Programme (ABPP) (Freeman et al. 2019).

The development of small-scale BGT is a complex problem regarding the complex nature of the factors influencing it. For the efficient adoption and diffusion of the technology in developing countries, it is important to understand the dynamics of the biogas system in order to appropriately design future interventions. In SSA, this technology consists of usually small-scale biogas digesters, mostly less than or equal to 10 cubic metres in volume and marred with several development constraints. These constraints affect the future development of the technology. From the market development point of view, this study aims to collect the PESTLE constraints and analyse them to reveal their implication for the future development of the technology. A systematic approach has been applied to reveal the link between studies on biogas technology from 2000 to 2020 in the SSA region.

The PESTLE analysis is one of the strategic management tools that can be used to determine for a given project, service or product, the inherent potential or risk in relation to its integral surrounding (Zahari & Romli 2019). It is used to identify the risks belonging to stated factors such as political, economic, social, technological, legal and environmental (Rastogi 2016). The PESTLE analytical approach is relevant to understanding the interaction of small-scale BGT and the SSA operation environment. Political and legal aspects underpin the enabling environment for the development of small-scale BGT. These factors establish the rights and assets of the stakeholders concerned. These factors are captured in policies and laws enacted by governments, regions and local communities influencing biogas technology development. The financial incentives contribute to attracting investors to biogas technology, including small-scale users. A robust, long-term institutional framework is also necessary to ensure the coordination and coherence of policies affecting energy, environment, and agricultural practices (Milbrandt & Uriarte 2012). Technical factors affecting small-scale biogas technology include the choice of biogas digesters, identification, availability of raw feedstuffs on a long-term basis and over the whole year, or supplies will be inconsistent, and people will lose confidence in the technology (WEC 2004). The Clean Development Mechanism (CDM) can promote renewable energy projects in developing economies to offset emission reduction commitments with the Kyoto Protocol in developed countries by investing in developing countries that can earn credits (WEC 2004).

2.2. Methodology

This study geographically covers the sub-Saharan African region. According to the United Nations, the region comprises forty-nine (49) countries located in the south of the Sahara Desert. A two-stage conceptual approach is applied to assess the impact of PESTLE constraints on the development of small-scale biogas technology in this region. Firstly, a systematic review is performed to identify and categorise the PESTLE constraints. Secondly, an impact assessment of the constraints is performed to reveal the implications of the factors on the future development of the technology in the region. The review considered publications for the period from 2000 to 2020.

2.2.1. Systematic literature review

A systematic review of peer-reviewed and grey literature on small-scale biogas technology in sub-Saharan Africa published from 2000 to 2020 was conducted. The political, economic, social, technological, legal and environmental constraints to the development of small-scale biogas technology were retrieved and categorised during the review. The following questions were investigated: What is the evolution of PESTLE factors affecting the development of small-scale biogas technology in sub-Saharan Africa? How do the constraints affect the adoption and diffusion of small-scale BGPs in the region? What are the impacts of the constraints on the sustainable development of small-scale BGP? The search strategy consisted of a combination of keywords such as 'sub-Saharan Africa biogas' were searched using Mendeley Desktop Version 1.19.4 to identify peer-reviewed literature on small-scale biogas plants in sub-Saharan Africa. This method collected titles and links of related articles from all sources on the world wide web. The titles of interest were collected, and the full articles were searched and downloaded from SCOPUS and Web of Science. Useful articles were stored on Mendeley Desktop Version 1.19.4. To identify the articles for specific countries, 'sub-Saharan Africa' in the keyword above was replaced by the name of the country. Furthermore, 'developing countries' was used as part of the keyword to gather useful literature. This further helped in the collection of more articles and references. Grey literature was obtained from various search engines on the world wide web. The optimisation of search results was achieved with Boolean operators. To identify country-specific grey literature search, keywords such as biogas AND 'name of country' were used.

2.2.2. Study selection

To filter the previously selected and stored literature in Mendeley Desktop Version 1.19.4, keywords such as 'biogas Africa' were used to sort the most useful articles. Then, more keywords like 'political, economic, social, technology, environment, legal, adoption, dissemination, and diffusion were used to describe the development of small-scale biogas technology in SSA. These words were used to sort and select the literature in the latter software. Finally, the rest of the literature not containing these keywords was used to obtain more information to substantiate the direct information previously collected. Figure 2.1 shows the stage stages of the selection of articles.

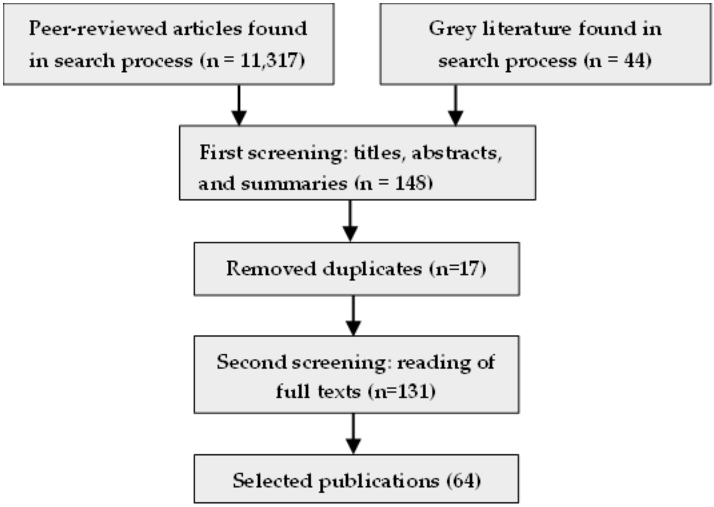


Figure 2.1. Stages of the selection of publications for the study

2.2.3. Inclusion and exclusion criteria

We read and assessed all the studies collected. The agreed-upon inclusion criteria were:

- studies focused on small-scale biogas technology in Africa and developing countries
- constraints to adoption and widespread dissemination or diffusion
- prospects of small-scale biogas plants in SSA

We excluded studies that dealt with large-scale or commercial plants. The exclusion is performed assuming that commercial biogas digesters are technically and economically better designed, constructed and managed than the small-scale biogas plants. Again, from the year 2000 to 2020, more small-scale BGPs have been disseminated as a means of alleviating poverty and hunger in SSA. Hence, the focus is on the small-scale digesters.

2.2.4. Data extraction

In handling the literature, they were sorted by year of publication in Mendeley Desktop Version 1.19.4, and the data were extracted systematically. The constraints were extracted from the eligible studies and categorised into political, economic, social, technological, legal and environmental. The year of publication (from 2000 to 2020) and the geographical boundary of the study (country, region or developing countries). The PESTLE data collected was arranged in a PESTLE table prepared in Microsoft Excel. Similar information about a given PESTLE aspect was discussed, and a common best-fit description or analysis was adopted.

2.2.5. Data analysis

The analytical technique used for this study was the PESTLE approach. Some of the PESTLE indicators shown in Figure 2.2 were retrieved from both peer-reviewed and grey literature. Manual search and reading were done to identify the key constraints and risks related to the development of small-scale biogas technology in SSA. For each of the PESTLE factors, the strengths/opportunities and the weaknesses/threats are identified. After the analysis, key recommendations were then proposed to re-orientate the sustainable development of the technology in the region.

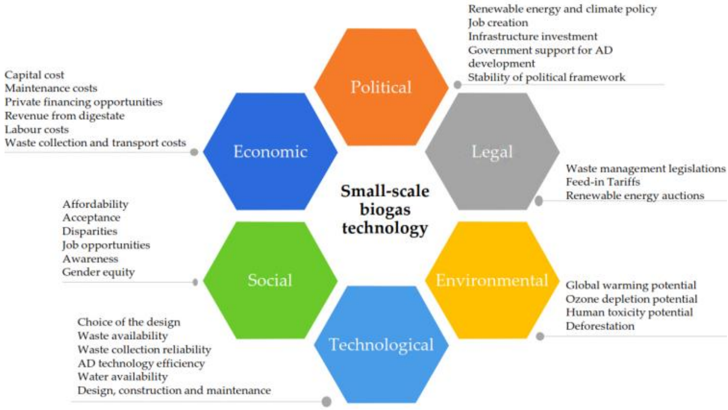


Figure 2.2. PESTLE factors affecting small-scale biogas technology

The impact of the PESTLE factors on the development of the small-scale biogas technology was based on the adoption and diffusion of the BGPs. Based on the categorisation of the PESTLE constraints, a ranking of the constraints was performed for the sub-regions of SSA, including the East, West, Southern and Central Africa. Weighting factors were used to represent the severity of the PESTLE constraints in each sub-region. The weight of each constraint was gotten by dividing the number of publications which reported on the constraint by the total number of publications (64), multiplied by 10. The higher the weighting factor, the higher the severity of the constraint and vice versa. The results were plotted against each constraint and presented in Figure 2.4.

2.3. Results and Discussion

2.3.1. Search results

From the literature search, a total of 11,361 publications were obtained. 11,317 publications were peer-reviewed articles, while 44 were grey literature obtained from various search engines of the World Wide Web. After screening the publications in two stages, 64 publications were selected based on their focus on the small-scale biogas plants in SSA or developing countries and the availability of PESTLE information in them. Out of these 64 publications, 58 were peer-reviewed, and 6 were grey. The distribution of the publications studied is shown in Table 2.1.

Countries of the region where national biogas programmes were implemented, produced documents with useful information to understand changes in the small-scale biogas technology. Unfortunately, academic publications were not found for the following countries: Cape Verde, Mauritania, Togo, Central African Republic, Equatorial Guinea, Sao Tomé and Principe, Liberia, Gambia, Benin, Mali, Togo, and Senegal. A variety of grey literature on these countries was found.

Table 2.1. Summary of the articles collected from the literature search

Region/ Country	Reference (s)	Σ
Africa, SSA	So et al. (2020), Surroop et al. (2019), Griffith-Jones et al. (2012), Roopnarain and Adeleke (2017a), Mandelli et al. (2014), Bamikole Amigun et al. (2011), Verbist (2018), Mulinda et al. (2013), Roopnarain and Adeleke (2017b), Kinyua et al. (2016), Cheng et al. (2014), Surendra et al. (2014), Maes and Verbist (2012), Ruane et al. (2010), Pollmann et al. (2014), Rupf et al. (2016), Smith et al. (2015), Rupf et al. (2015), Mwirigi et al. (2014b), Mohammed et al., (2013), Parawira (2009), Gebreegziabher et al. (2014), Mwirigi et al. (2014), Nevzorova and Kutcherov (2019), Terrapon-Pfaff et al. (2018), Amigun and Blottnitz (2009)	26
East Africa	Walekhwa et al. (2009), Wassie and Adaramola (2019) Karanja and Gasparatos (2019), Mwirigi et al. (2009), Kamp and Forn (2016), Mengistu et al. (2015b), Kamp and Forn (2015), Sarakikya (2015), Mwakaje (2008), Omer (2005), Godfrey (2012), (Wilson, 2007)	12
Central Africa	Muh et al. (2018), Tangka et al. (2016), Kimengsi (2015), Balgah et al. (2018)	4
Southern Africa	Walwyn and Brent (2015), Boyd (2012), Msibi and Kornelius (2017), Rasimphi and Tinarwo (2020), Chirambo (2016), Aliyu et al. (2018), Shane et al. (2017), Shane et al. (2016), Jingura et al. (2013), Mokhtar, et al. (2013), Kemausuor et al. (2011), Painuly and Fenhann (2002)	12
West Africa	Aliyu et al. (2015), Ishola et al. (2013), Akinbami et al. (2001), Okello et al. (2013), Mas’ud et al. (2015), Ohimain (2013), Ituen et al. (2009), Adeoti et al. (2000), Osei-Marfo et al. (2018), Kemausuor et al. (2015).	10
Total		64

2.3.2. PESTLE constraints to the development of small-scale biogas technology in SSA

Despite the market share of renewables in SSA, small-scale biogas technology remains one of the least exploited regarding the available potential. Barriers to their enhanced development are at all levels - in practical policy attitudes, economic sphere, social, technology management, environment and legislation. The results of the PESTLE factors are presented below.

2.3.3. Political

Political constraints to the development of small-scale BGT are still evident. SSA is still faced with several bottlenecks regarding the consideration of small-scale BGT in national energy policies. Before the year 2000, no SSA country had a bioenergy policy. Despite the advances made by some countries in the development of renewable and/or bioenergy policies, political support for small-scale BGT development is still inadequate. Lessons learned from the development of biogas programmes in India, China and Nepal enabled South Africa to develop its small-scale biogas market (Austin 2003). In 2009, Parawira (2009) still identified that poorly informed and uninformed authorities and policymakers in SSA led to gaps in the formulation of renewable energy policies. As part of the experimentation process, SNV, Heifer International and Hivos assisted national governments of the region to develop and implement biogas programmes. The African bioenergy policy framework and guidelines have existed since 2013 (AUC-ECA 2013). Nevertheless, countries have not made progress in adopting or implementing these policy instruments. The passivity of some governments remains a threat to promoting biogas technology (Pollmann et al. 2014). Bottom-up approaches are required for the significant inclusion of small-scale technology in the national renewable energy policies. Most development policy frameworks in the region have no direct strategy for the development of small-scale biogas technology. The stability of political framework and transparency is therefore required for the development of small-scale biogas technology. In 2017, bioenergy provided 176,000 jobs in the region. Biogas technology expansion opens employment opportunities for masons, plumbers, civil engineers, and agronomists (Mengistu et al. 2015). The number of these jobs created has not been realistically tracked. Socio-political instability in some SSA countries has led to the low rate of adoption and dissemination of these small-scale biogas plants. For example, Burundi was affected by the war between 1993 and 2000 (SE4All 2013). Since then, they have been reconstructing the country and pending significant interest in developing the technology. Under a stable socio-political situation, the biogas potential is an asset.

2.3.4. Economic

The primary economic constraint to the development of the small-scale BGT is the inadequate investment cost. The average cost of small-scale biogas plants in some SSA countries is shown in Table 2.2**.** The cost of the technology is mainly dependent on the plant's geographical location (Amigun & Von Blottnitz 2010). Boyd (2012) reported on South Africa's inadequate access to finance. Generally, financial institutions in the region still lack financing structures for small biogas projects (Parawira 2009). The revenue from the digestate, otherwise referred to as organic fertiliser, is widely not yet estimated for most SSA countries. In South

Africa, Mdlambuzi and Tsubo (2021) revealed that the co-application of digestate and mineral fertiliser in crop production reduced farming costs. There is an information deficit on the economic viability of available biomass and waste resources (So et al. 2020). Due to the clustering of poor or average homes in some countries, construction space is seen as a constraint to the adoption of small-scale BGPs. This was identified in the case of Nigeria by Akinbami et al. (2001). Mwirigi et al. (2014) in a study in Uganda, stated that one of the factors affecting the adoption of small-scale biogas technology is the small size of landholdings. By 2017, Kenya had made the most progress toward establishing viable biogas plant markets, through hosting companies with prefabricated digesters and establishing 22 marketing hubs, linking rural institutions to local enterprises and finance (Clemens et al. 2018). Makai and Molinas (2013) revealed that the payback period of small-scale BGPs in Zambia is 3.25 to 3.75 years. According to Kabyanga et al. (2018), many of the biogas designs promoted in Uganda proved to be too expensive for the average Ugandan to afford. They added that a cheaper flexible balloon digester was affordable, but there is no evidence of the design's economic viability. Generally, small-scale biogas users still find it challenging to afford the complete small-scale BGPs. Parawira (2009) recommended the need to provide loans and subsidies to encourage and promote biogas technology. Market incentives for biogas technology include 'soft' loans, direct and indirect subsidies, and international funding schemes through the Clean Development Mechanism fund and Joint Implementation Programme' (Surroop et al. 2019).

Table 2.2. Average costs of small-scale biogas plants in some SSA countries

Location	Capacity (m^3)	Year constructed	Cost (US$)	Source
Burkina Faso	6	2004	1,209	
Ghana	6	2004	1,358	Osei-Marfo et al. (2018)
Ghana	6	2011	2,189	
Ghana	6	2015	851	
Ghana	10	2011	3,169	
Kenya	8	2004	2,973	
Uganda	6	2004	1,005	
Rwanda	6	2007	859	Amigun and Blottnitz (2010);
South Africa	6	2007	1149	Amigun and Blottnitz (2010)

Akinbami et al. (2001) recommended that using local materials reduce construction costs, which constitute up to 65% of the total investment costs. Labour and other costs amounted to an additional 35% of the cost (Akinbami et al. 2001). In some cases, household labour was used to reduce costs (Osei-Marfo et al. 2018).

Biogas technology has been scaled up in SSA during the last two decades with programme funds mainly from SNV, Hivos and Heifer International. The sustainability of the adoptions is not ensured because of the various constraints after the programmes. One possible, despite the controversial approach to increasing the adoption of small-scale biogas technology out of the programme funds is to utilise the available funds that a household possesses, rather than targeting the very poor households (Smith et al. 2011). Information dissemination on the successful implementation of the technology by farmers to their counterparts proves to be the best tool to promote biogas use (Berhe et al. 2017). Biogas produced with small-scale digesters is used in different appliances including biogas stoves (one and two burners), water heater (Mwirigi et al. 2014a), biogas lamp (Khandelwal 2009; Mwirigi et al. 2014a) and biogas electricity generator (Tangka et al. 2016; Mwirigi et al. 2014a).

2.3.5. Social

At the beginning of the year 2000, socio-cultural constraints still impacted the uptake and dissemination of the small-scale BGPs. In Nigeria, the inertia toward changes, especially when it involves an unfamiliar (even though simple) technology, was a potential barrier to adopting and disseminating biogas technology (Akinbami et al. 2001). Walekhwa et al. (2009) later in Uganda assessed Uganda's acceptance of small-scale BGT and discovered that the development and acceptance of biogas technology largely depended on exploiting its technological opportunities over the existing technologies. This led to poor ownership by the users (Parawira 2009). In Rwanda, Tanzania and Malawi, it was believed that training and skills development of communities would alleviate the lack of user acceptance (Barry et al. 2011). Improving the skills base of the community was helpful in maintaining the technology. The dissemination approach integrating capacity building, governance and integrated development was adopted by SNV (Ghimire 2013a). In 2014, low levels of awareness of the potential uses of biogas and the small size of landholdings limited the number of different types of land use unless the uses were complimentary (Mwirigi et al. 2014). In Uganda, an increase in age and level of education were inversely related to adoption while the availability of traditional fuels and the increase in household size positively impacted the acceptance of the technology (Mwirigi et al. 2014). The low levels of education and income of women were the leading causes of their limited or no involvement in the decisions to adopt BGPs. The decision to install the BGPs was mainly made by the male household heads who control resources and their allocation (Mwirigi et al. 2014). Over the past two decades, biogas stakeholders have made significant efforts to create awareness of the role of small-scale BGT. In the region, the technology is generally accepted by people of different socio-cultural and religious backgrounds. However, affordability and gender constraints still need to be addressed for wider adoption of the technology. Nevzorova and Kutcherov (2019) still identified a lack of acceptance as one of the constraints to the development of small-scale BGT in SSA. A study by Lemma et al. (2020) in southern Ethiopia showed that in households, 92.5% of biogas users and 77.5% of non-users tend to have a positive attitude towards biogas technology. About 52.5% of the non-users did not have adequate information, while the installation costs deterred 25% of the non-users.

2.3.6. Technological

Technical potential of small-scale BGPs in SSA

The technical potential is defined as the number of households that can meet the two basic requirements - sufficient availability of both dung and water – to operate a biogas plant (SNV 2018). The first estimation of the technical potential of domestic or household biogas in Africa was done in 2007 by Heegde and Sonder (2007). Two leading indicators were used included the number of households with access to water and the number of domestic cattle per household. The small-scale biogas potential of SSA is continuously being assessed. The latest study by SNV (2018) showed that the technical potential for household biogas plants in Africa is 32.9 million installations. By 2012, the total number of constructed BGPs had risen to nearly 23,000. By December 2018, this number rose to 75,561 with the involvement of other agencies under the umbrella of the Africa Biogas Partnership Programme (ABPP) (Freeman et al. 2019). This shows that SSA has exploited less than 1 per cent of its technical biogas potential. Figure 2.3 shows the quintile distribution of the technical potential of household biogas plants in SSA.

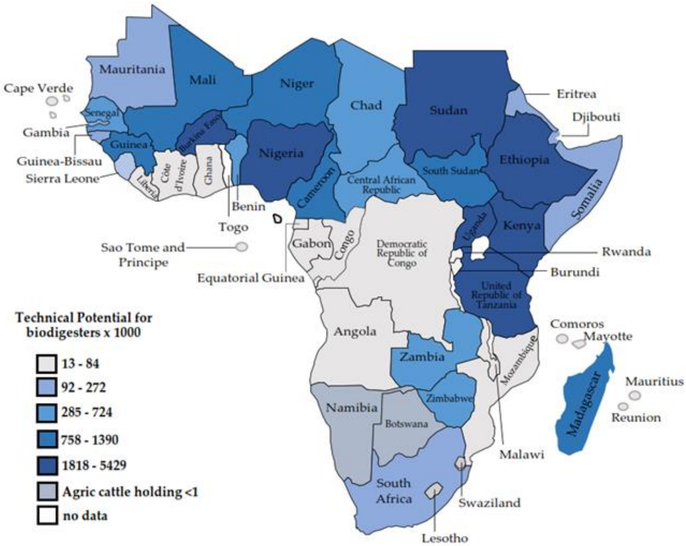


Figure 2.3. Quintile division of the technical potential of household biogas plants by country in SSA
Source: Data from SNV (2018).

Choice of digester design

There exist three main philosophies commonly applied in the design of household or small-scale BGPs, namely the floating drum, the fixed dome, and the flexible balloon digester (Jansen & Rutz 2012). Prefabricated biogas digesters following the above philosophies are also present in the region (Cheng et al. 2014). Biogas plants' size is based upon: (i) the (daily) amount of available feeding material; and (ii) the biogas requirement of the family (Freeman et al. 2019). Some of the major constraints identified include the wrong selection of the design and size of the digester. This contributes to the operation failure in some cases. Construction of the digesters with low-quality materials has resulted in short life and efficient biogas plants.

Since the first introduction of small-scale biogas technology in SSA, the conventional fixed dome and floating biogas digester were promoted. The fixed-dome design is accepted by most users as the most viable design that is affordable and reliable for the domestic market. In SSA like other parts of the world like India, the switch from the floating drum design to the fixed dome design is increasing (Jansen & Rutz 2012). Due to inadequate finance to purchase these plants, the private sector has developed low-cost biogas plants, including the Flexi-biogas in Kenya, while others have recycled plastic containers into biogas digesters. From 2011 to 2014, IFAD and Biogas International distributed 500 Flexi-Biogas System (FBS) units to rural Kenyan households (Sovacool et al. 2015). The flexible balloon biogas digester design is not suitable for a programme-based approach to digester installations where a predefined financing scheme (including subsidies linked to quality assurance measures and long-term production of voluntary or certified emissions reductions).

Table 2.3. Types of digesters

Type of digester	Advantages	Disadvantages	Source
Fixed dome digester	- eliminates the use of costly mild steel gasholder, - relatively low installation cost (about two-thirds of the cost of the floating drum digester), - does not have moving parts, - does not have rusting steel parts, - long lifespan (20 years or more), - possible underground construction, - saves space, - creates local employment during construction,	- digesters are usually not gastight (porosity and cracks). The gas tightness is a problem that pertains only to the constructed systems and not prefabricated systems, - gas pressure fluctuates substantially.	(Mulinda et al. 2013; Jansen & Rutz 2012).
Floating drum	- has a simple operation design, - operates at constant gas pressure, and the volume of stored gas is visible directly on the	- high installation cost (up to 50% greater than that of a fixed dome digester), - uses many steel parts that can easily corrode, leading to short lifespan	(Mulinda et al. 2013; Jansen & Rutz 2012).

		(up to 15 years; in tropical regions and about 5 years for the drum), - requires regular maintenance costs due to painting.	
Polyethylene digesters (including high density polyethylene digesters)	- technically cheapest and simple design to install - easy transportation, - shallow construction - high digester temperatures, - easy cleaning, emptying, and maintenance.	- short lifespan (about 5 years), - High risk of damage, - no real local employment creation, little scope for self-help - low gas storage is a limitation	(Kabyanga et al. 2018; Jansen & Rutz 2012)

Therefore, long-term functionality is needed. Balloon BGPs are preferable wherever the balloon surface is not exposed or has the likely risk of damage, especially in areas where the temperature is constantly high (Jansen & Rutz 2012).

Anaerobic digestion efficiency

Biogas production through anaerobic digestion of organic waste using small-scale BGPs is a continuous learning process in the regions. Parawira (2009) in Uganda identified that household biogas digesters in SSA, usually lack facilities to remove sand, stones and other non-digestible materials, which accumulate over years of use, thereby decreasing the volume of the digesters, hence reducing efficiency**.** SSA has a suitable tropical climate in most parts of the region, which favours the natural production of biogas (Rupf et al. 2015). From poor designs to poor operation and maintenance, followed by the lack of inadequate monitoring devices, most of the small-scale BGPs rely on the local climatic conditions. To realise the full potential of biogas, the efficiency of end-use appliances must also be improved and adapted to local cooking conditions, as has been done with other cooking technologies (Freeman et al. 2019). Co-digestion has also been proven to ease or improve biogas, e.g. the case of a mixture of poultry/cow dung/water hyacinth at the Songhai Farm in Burkina Faso.

Waste availability

In SSA, the feedstock for biogas production is mainly manure (faecal waste) from livestock, e.g. cattle, sheep, goats, horses, donkeys, rabbits and chickens, but also from humans if culturally acceptable (Orskov et al. 2014). The biogas potentials of the available animal and agricultural feedstocks have not been thoroughly researched. Karekezi et al. (2003)

stated that despite the proof of the viability of small-scale biogas plants, dung collection proved more problematic than anticipated, particularly for farmers who did not keep their livestock penned in one location. More R&D is also needed to explore better substrates to boost the efficiency and performance of the biogas plants. Land management and the method of rearing are also affecting the availability of feedstocks. For example, the results of the nationally representative household surveys in Ethiopia, Kenya, Rwanda, Mozambique and Zambia, concluded that farm sizes in Africa are declining over time, with approximately 25% of agricultural households being virtually landless, controlling less than 0.1 ha $caput^{-1}$, the largest part of the variation in farm sizes occurring within, rather than between villages. Households controlling such a low area of land may be limited in the livestock they can manage, which may, in turn, limit their potential to run a biogas digester (Orskov et al. 2014).

Water availability for anaerobic digestion across the region
Mwirigi et al. (2014) identified hurdles to the wider adoption of small-scale BGT in SSA, including limited access to water. In South Africa, Calendar et al. (2007) revealed a common misperception that access to water is a constraint on the use of BGT at the household level. Since each family uses water every day, this same water can easily be directed to the biogas digester. According to Griffith-Jones et al. (2012), households in SSA were 28.2% and 125.2% more likely to have access to improved water sources in 2000 - 2005 and 2010-2015, respectively, than in 1990-1995. The World Bank (2020) reports that 27% of the population of SSA have access to safely managed drinking water.

Design, construction and maintenance

In SSA, inexperienced technicians and consultants have resulted in poor-quality BGPs. This is a result of poor selection of construction materials (Parawira 2009). This is due to inadequate technical know-how in the design and construction of small-scale biogas plants (So et al. 2020) and flawed or wrong operation and maintenance culture (So et al. 2020). The optimisation of the BGP design process has been constrained by inadequate knowledge, even at the level of research institutes and universities (Parawira 2009). A study by Berhe et al. (2017) in Ethiopia's Tigray region showed that 58.1% (of a total of 3600 BGPs) of the installed BGPs were non-operational due to incomplete installation, other technical problems, and limited supervision. Waste collection reliability is still not measured. Where the biogas systems are properly designed, they have contributed to the reduction of fuelwood collection time by women and children in the region.

2.3.7. Legal

Several disputes persist in sub-Saharan Africa regarding the sustainable management of natural resources such as water, land and agricultural wastes. In South Africa, Du Plessis (2003) identified that no legal measures were dealing with the collection of dung, except in the case of the Gas Act of 2002, which excludes small biogas projects in rural communities. Some countries in sub-Saharan Africa have relatively successfully scaled up renewable energy through changing energy market structures and introduced incentives (Griffith-Jones et al. 2012). In Kenya, biogas equipment such as stoves, other appliances, and prefabricated digesters may be exempted from import tax. Notwithstanding, interviews with biogas stakeholders (mainly entrepreneurs) indicate that the exemption can only apply to the entire shipping containers of appliances and, therefore, does not benefit small enterprises. Moreover, the process of obtaining duty-free status is unclear to local entrepreneurs in the region. No tax exemptions exist in Tanzania and Uganda (Clemens et al. 2018), as well as in most other countries of the region. According to IRENA (2018), renewable energy auctions can be successfully implemented in South Africa, Uganda and Zambia. Only large-scale biogas technology producing marketable electricity can benefit from these auctions. Small-scale biogas technology still lacks cost-legal frameworks for development incentives in the region.

2.3.8. Environmental

The BGPs in SSA are multi-functional depending on the reason for construction, such as sanitation, energy recovery, management of waste and environmental protection (Mulinda et al. 2013). The unsustainable use of fuelwood biomass accelerated deforestation and led to soil erosion, desertification and an increased risk of flooding and biodiversity loss (Parawira 2009). In Africa, biogas production reduced deforestation due to fuelwood demand between 6 and 36% in 2010 and a potential between 4 and 26% by 2030 (Matthews et al. 2014). The Clean Development Mechanism (CDM) is inadequately applied to promote renewables projects in SSA to offset emission reduction commitments under the Kyoto protocol. By investing in the latter, developing countries can earn credits (WEC 2004). Venkata et al. (2015), per 2010 data, indicated that household air pollution mortality and morbidity led to 14% of the deaths in SSA in an affected population of 3.5 million. This also led to a 24% Disability-Adjusted Life Year

(DALY). There is a need to quantify the environmental benefits of small-scale biogas in SSA. For example, in Ethiopia, each household BGP has the potential to reduce about 6024 kg CO_2e per year of GHG emissions (Lemma et al. 2020). Also, around 13 kg CO_2e/tonne can be saved when digestate replaces mineral fertiliser (Litmanen & Kirchmeyr 2014). This data is absent for most countries of the region. Under the Paris Agreement on Climate Change, all SSA countries have included renewable energy actions (covering all technologies and end-use applications) as commitments to tackle climate change as well as spur economic growth (UNECA 2018). Despite the ratification agreement by all SSA countries, there is an inadequate effort being made by governments to develop small-scale biogas plants as part of the national environmental strategies.

2.4. Impact of PESTLE constraints

Figure 2.4. shows that the constraints in decreasing order of severity are economical, technical, political, social, environmental and legal. Considering the most significant constraint (economic constraint), the Southern Africa sub-region has lower economic constraints than any other region in the SSA region. The affordability of the small-scale BGPs is the lowest in East Africa and highest in Southern Africa. Most of the users of small-scale BGPs in the region are rural dwellers depending on but not limited to the household income to fund the small-scale biogas projects. Owners of agricultural and livestock farms are more likely to afford and sustain the technology. Incentives are still needed from private, public and international institutions or organisations to finance this technology for resource-poor households. The implementation

of climate change agreements (including the clean development mechanism) on the reduction of GHG emissions remains a potential source of funding for local biogas projects. A useful action would be the development of context-based business models and more job creation that recognise the key sustainability issues of the technology. Political constraints have greatly reduced due to the willingness of the public and partner organisations to develop the technology. The absence of bioenergy policies in some countries is still constraining the development of the technology. The gaps in bioenergy policy can be filled by elaborating new policies or updating existing ones based on the changes at the different development levels – micro, regime and landscape (directly addressing issues related to biogas technology, especially in rural areas). The appropriateness of the policy instrument needs to be the focus of the process in order to address specific rural, country or regional specificities. The African bioenergy policy framework and guidelines have existed since 2013 (AUC-ECA 2013). This policy document provides the key aspects that should be included in bioenergy policies. The current status of the country's bioenergy policy elaboration is not well known due to inadequate tracking of progress data. The central African sub-region is still lagging in relation to the other regions in reducing policy constraints. This can justify the low uptake and dissemination in the sub-region. Regarding social impacts, inadequate awareness and gender mainstreaming in biogas projects across the region have reduced the social impacts of the technology. Guidance on gender mainstreaming in small-scale biogas projects in the region was only elaborated in 2010 using Kenya as the case study (Energia & Hivos 2010). In 2022 (about 12 years later), the region is still to make strides regarding this issue. Due to slow policy changes, access to and control of land have limited women's control over technology. Future interventions in small-scale biogas technology dissemination require national and regional strategies to increase the significant involvement of all genders in the development process. Technical constraints have exerted a significant influence on the efficiency, reliability and operation of the BGPs with variable inputs. This has been caused in part by the lack of quality standards in the design, construction, operation and maintenance of the BGPs. The role of research and development is indispensable to reduce these defects. Legal issues, including standards and regulations, where addressed, reduced the institutional burden on the adopters. These are more and more needed to increase users' willingness and engagement in developing the technology. Due to the inability of the technology to meet household energy needs, especially for cooking, deforestation reduction and indoor pollution (with devastating health consequences) have persisted.

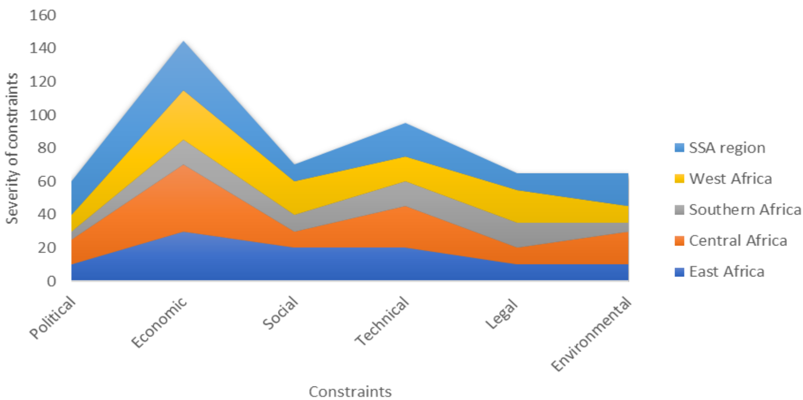


Figure 2.4. Severity of PESTLE constraints in SSA

2.5. Policy implications

This study deduces that the core action to reduce the PESTLE constraints is to improve the financing of the technology. Some elements to consider are providing subsidies, mobilising international climate funds, tax exemptions and promoting local entrepreneurship involving more women. Local finance institutions should be motivated to develop financing schemes for small-scale biogas projects. Extension services should be designed to enable users to sustain the technology. This can be achieved through the socio-technical design of rural biogas energy systems. This will complement the smooth transition to the technology as targeted by the SDG7 by 2030 and the Agenda 2063 of the African Union. Most of the reported biogas plants in the region are programmatic (constructed through demonstration and foreign-funded projects in partnership with governments). There is still low reporting on the actual built capacity (some household-funded biogas plants have not been reported). This highlights the need to consider improving data management at local, national and regional levels. Developing the human capacity to develop the technology is necessary. Finally, there is a need to promote local research and transfer of good practices from similar projects in other parts of the world, including Nepal, Vietnam, China and India.

2.6. Conclusion

Despite the introduction of biogas technology in SSA in the mid-20th century, its market share compared to other renewable energy sources is still lower. Reforms are still needed to boost its adoption and dissemination. The development of small-scale biogas technology in SSA is still influenced by political, economic, social, technological, legal and environmental constraints. In addition, institutional and geo-spatial factors influence this technology. The development of small-scale biogas technology in SSA still requires appropriate financing schemes and technological innovation to increase the efficiency, reliability and performance. Over the past two decades, civil society organisations (CSOs), including SNV, Hivos and Heifer International have been the leading promoters of the technology in SSA. This has been done through programme budgets which seem to lack follow up and sustainability of the implemented actions. The ABPP is currently fostering some of the actions of the later organisations and partners. The PESTLE inadequacies still require many governmental and CSO responses to boost the adoption and dissemination of the technology in the region.

References

Adeoti O, Ilori MO, Oyebisi TO, Adekoya LO. 2000. Engineering design and economic evaluation of a family-sized biogas project in Nigeria. Technovation. https://doi.org/10.1016/S0166-4972(99)00105-4

Akinbami JF, Ilori M, Oyebisi T, Akinwumi I, Adeoti O. 2001. Biogas energy use in Nigeria: current status, future prospects and policy implications. Renewable and Sustainable Energy Reviews, 5(1), 97–112. https://doi.org/10.1016/S1364-0321(00)00005-8

Al S. 2011. DFID Interdisciplinary Expert Workshop on the Potential of Small-Scale Biogas Digesters in Sub-Saharan Africa -. Current, 16–18.

Aliyu AK, Modu B, Tan CW. 2018. A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. Renewable and Sustainable Energy Reviews, 81 (June 2017), 2502–2518. doi: 10.1016/j.rser.2017.06.055

Aliyu AS, Dada JO, Adam IK. 2015. Current status and future prospects of renewable energy in Nigeria. Renewable and Sustainable Energy Reviews, 48, 336–346. doi: 10.1016/j.rser.2015.03.098

Amigun B, Von Blottnitz H. 2009. Capital cost prediction for biogas installations in Africa: Lang factor approach. Environmental Progress and Sustainable Energy. doi: 10.1002/ep.10341

Amigun B, Von Blottnitz H. 2010. Capacity-cost and location-cost analyses for biogas plants in Africa. Resources, Conservation and Recycling, 55(1), 63–73. doi: 10.1016/j.resconrec.2010.07.004

Amigun B, Musango JK, Stafford W. 2011. Biofuels and sustainability in Africa. Renewable and Sustainable Energy Reviews, 15(2), 1360–1372. doi: 10.1016/j.rser.2010.10.015

Austin G. 2003. Biogas energy and sanitation provision in South Africa. ESI Africa.

Balgah RA, Mbue IN, Ngwa KA. 2018. The impacts of renewable energy on livelihoods : A case study of biogas adoption in Cameroon. 7(1), 220–239.

Barry ML, Steyn H, Brent A. 2011. Selection of renewable energy technologies for Africa: Eight case studies in Rwanda, Tanzania and Malawi. Renewable Energy, 36(11), 2845–2852. doi: 10.1016/j.renene.2011.04.016

Berhe TG, Tesfahuney RG, Desta GA, Mekonnen LS. 2017. Biogas Plant Distribution for Rural Household Sustainable Energy Supply in Africa. Energy and Policy Research, 4(1), 10–20. doi: 10.1080/23815639.2017.1280432

Boyd A. 2012. Informing international UNFCCC technology mechanisms from the ground up: Using biogas technology in South Africa as a case study to evaluate the usefulness of potential elements of an international technology agreement in the UNFCCC negotiations process. Energy Policy, 51, 301–311. doi: 10.1016/j.enpol.2012.08.020

Buysman E. 2015. Biogas and household air quality Study on Household Air Quality and Estimated. November.

Calendar E, Rates E, Us A, Us C. 2007. Biogas energy and sanitation provision in South Africa Biogas energy and sanitation provision in South Africa By Greg Austin , Director , Biogas Technology Africa Biogas energy and sanitation provision in South Africa. November 2000, 2000–2002.

Cheng S, Li Z, Mang HP, Huba EM, Gao R, Wang X. 2014.

Development and application of prefabricated biogas digesters in developing countries. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2014.03.035

Chirambo D. 2016. Addressing the renewable energy financing gap in Africa to promote universal energy access: Integrated renewable energy financing in Malawi. Renewable and Sustainable Energy Reviews, 62, 793–803. doi: 10.1016/j.rser.2016.05.046

Clemens H, Bailis R, Nyambane A, Ndung V. 2018. Energy for Sustainable Development Africa Biogas Partnership Program : A review of clean cooking implementation through market development in East Africa. Energy for Sustainable Development, 46, 23–31. doi: 10.1016/j.esd.2018.05.012

Du Plessis W. 2003. Energy law and environmental protection in South Africa. Sustainable World, 7, 103–112.

Freeman KK, Seppala JAK. 2019. The power of dung Lessons learned from. World Bank Group Agriculture.

Gebreegziabher Z, Naik L, Melamu R, Balana BB. 2014. Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa. Biomass and Bioenergy, 70, 130–140. doi: 10.1016/j.biombioe.2014.02.036

Ghimire PC. 2013. SNV supported domestic biogas programmes in Asia and Africa. Renewable Energy. doi: 10.1016/j.renene.2012.01.058

Godfrey A. 2012. Dairy Farming and the Stagnated Biogas Use in Rungwe District, Tanzania: An Investigation of the Constraining Factors. In Biogas. doi: 10.5772/32012

Griffith-Jones S, Ocampo JA, Spratt S. 2012. Financing renewable energy in developing countries: Drivers and bariers for sub-Saharan Africa. February, 1–55. Available from http://www.unepfi.org/fileadmin/documents/Financing_Renewable_Energy_in_subSaharan_Africa.pdf

IRENA. 2017. Biogas for domestic cooking. Technology brief, International Renewable Energy Agency, Abu Dhabi.

IRENA. 2018a. Renewable energy auctions: Cases from sub-Saharan Africa. In /publications/2018/Apr/Renewable-energy-auctions-Cases-from-sub-Saharan-Africa. http://irena.org/publications/2018/Apr/Renewable-energy-auctions-Cases-from-sub-Saharan-Africa

IRENA. 2018b. Sustainable rural bioenergy solutions in sub-Saharan Africa : A collection of good practices, International Renewable Energy Agency, Abu Dhabi.

Ishola MM, Brandberg T, Sanni SA, Taherzadeh MJ. 2013. Biofuels in Nigeria: A critical and strategic evaluation. In Renewable Energy. doi: 10.1016/j.renene.2012.12.021

Ituen EE, John NM, Bassey BE. 2009. Biogas production from organic waste in Akwa Ibom State of Nigeria. Appropriate Technologies for Environmental Protection in the Developing World - Selected Papers from ERTEP 2007. doi: 10.1007/978-1-4020-9139-1_11

Jingura RM, Musademba D, Kamusoko R. 2013. A review of the state of biomass energy technologies in Zimbabwe. Renewable and Sustainable Energy Reviews, 26, 652–659. doi: 10.1016/j.rser.2013.05.036

Kabyanga M, Balana BB, Mugisha J. Walekhwa PN, Smith J, Glenk K. 2018. Economic potential of flexible balloon biogas digester among smallholder farmers: A case study from Uganda. Renewable Energy, 120, 392–400. doi:

10.1016/j.renene.2017.12.103

Kamp LM, Forn EB. 2016. Ethiopia’s emerging domestic biogas sector: Current status, bottlenecks and drivers. Renewable and Sustainable Energy Reviews, 60, 475–488. doi: 10.1016/j.rser.2016.01.068

Kamp LM, Forn EB. 2015. Bottlenecks and drivers in Ethiopia’s domestic biogas sector. IAMOT 2015 - 24th International Association for Management of Technology Conference: Technology, Innovation and Management for Sustainable Growth, Proceedings.

Karanja A, Gasparatos A. 2019. Adoption and impacts of clean bioenergy cookstoves in Kenya. Renewable and Sustainable Energy Reviews, 102 (December 2018), 285–306. doi: 10.1016/j.rser.2018.12.006

Karekezi S, Kithyoma W, Initiative E. 2003. Renewable energy development. Workshop on African Energy Experts on Operationalizing the NEPAD Energy Initiative, June, 2–4.

Kemausuor F, Addo A, Darkwah L. 2015. Technical and Socioeconomic Potential of Biogas from Cassava Waste in Ghana. Biotechnology Research International. doi: 10.1155/2015/828576

Kemausuor F, Obeng GY, Brew-Hammond A, Duker A. 2011. A review of trends, policies and plans for increasing energy access in Ghana. Renewable and Sustainable Energy Reviews, 15 (9), 5143–5154. doi: 10.1016/j.rser.2011.07.041

Khandelwal KC, GVK. 2009. Popular Summary of the Test Reports on Biogas Stoves and Lamps prepared by testing institutes in China, India and the Netherlands. Snv.

Kimengsi JN. 2015. Adopting the Use of Biogas as a Renewable Energy Source in Bui Division of Cameroon :

Challenges and Blueprints *. Renewable Energy Law and Policy : RELP.
Kinyua MN, Rowse LE, Ergas SJ. 2016. Review of small-scale tubular anaerobic digesters treating livestock waste in the developing world. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2015.12.324
Lemma B, Ararso K, Evangelista PH. 2020. Attitude towards biogas technology, use and prospects for greenhouse gas emission reduction in southern Ethiopia. Journal of Cleaner Production, xxxx, 124608. doi: 10.1016/j.jclepro.2020.124608
Litmanen S, Kirchmeyr F. 2014. Effluent Treatment Plant The Use of Digestate as an Organic Fertiliser. April, 3–7. Available from http://www.envirotech-online.com/articles/water-wastewater/17/susanna_litmanen_franz_kirchmeyr/the_use_of_digestate_as_an_organic_fertiliser/1593/
Maes WH, Verbist B. 2012. Increasing the sustainability of household cooking in developing countries: Policy implications. Renewable and Sustainable Energy Reviews, 16 (6), 4204–4221. doi: 10.1016/j.rser.2012.03.031
Makai L, Molinas M. 2013. Biogas - An alternative household cooking technique for Zambia. 2013 IEEE Global Humanitarian Technology Conference (GHTC), 17–22. doi: 10.1109/GHTC.2013.6713647
Mandelli S, Barbieri J, Mattarolo L, Colombo E. 2014. Sustainable energy in Africa: A comprehensive data and policies review. Renewable and Sustainable Energy Reviews, 37, 656–686. doi: 10.1016/j.rser.2014.05.069
Mang H, Li Z. 2010. Technology review of biogas sanitation.Biogas sanitation for blackwater, brown water,

or for excreta treatment and reuse in developing countries. Deutsche Gesellschaft für Internationale Zusammenarbeit. Suatainable sanitation - ecosan program. Postfach 5180, 65726 Eschborn, Germany.

Martinot E, Chaurey A, Lew D, Moreira JR, Wamukonya N. 2002. Renewable energy markets in developing countries. Annual Review of Energy and the Environment, 27, 309–348. doi: 10.1146/annurev.energy.27.122001.083444

Mas'ud AA, Wirba A, Muhammad-Sukki F, Mas'ud IA, Munir AB, Md Yunus N. 2015. An assessment of renewable energy readiness in Africa: Case study of Nigeria and Cameroon. Renewable and Sustainable Energy Reviews, 51, 775–784. doi: 10.1016/j.rser.2015.06.045

Matthews RB, Subedi M, Matthews R, Pogson M, Abegaz A. 2014. Can biogas digesters help to reduce deforestation in Africa ? ScienceDirect Can biogas digesters help to reduce deforestation in Africa ? Biomass and Bioenergy, May 2019. doi: 10.1016/j.biombioe.2014.02.029

Mdlambuzi T, Tsubo M. 2021. Maize (Zea Mays L) production in a semiarid area of South Africa from co-application of biogas slurry with chemical fertilizer and effects on soil quality. Mdlambuzi T. Communications in Soil Science and Plant Analysis, 00 (March), 1–10. doi: 10.1080/00103624.2022.2072512

Mengistu MG, Simane B, Eshete G, Workneh TS. 2015a. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. Renewable and Sustainable Energy Reviews, 48, 306–316. doi: 10.1016/j.rser.2015.04.026

Mengistu MG, Simane B, Eshete G, Workneh TS. 2015b. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. Renewable and Sustainable Energy Reviews, 48, 306–316. doi: 10.1016/j.rser.2015.04.026

Mohammed YS, Mokhtar AS, Bashir N, Saidur R. 2013. An overview of agricultural biomass for decentralized rural energy in Ghana. Renewable and Sustainable Energy Reviews, 20, 15–25. doi: 10.1016/j.rser.2012.11.047

Mohammed YS, Mustafa MW, Bashir N. 2013. Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa. Renewable and Sustainable Energy Reviews, 27, 453–463. doi: 10.1016/j.rser.2013.06.044

Msibi SS, Kornelius G. 2017. Potential for domestic biogas as household energy supply in South Africa. Journal of Energy in Southern Africa, 28 (2), 1. doi: 10.17159/2413-3051/2017/v28i2a1754

Muh E, Amara S, Tabet F. 2018. Sustainable energy policies in Cameroon: A holistic overview. Renewable and Sustainable Energy Reviews, 82 (October 2017), 3420–3429. doi: 10.1016/j.rser.2017.10.049

Mulinda C, Hu Q, Pan K. 2013. Dissemination and Problems of African Biogas Technology. Energy and Power Engineering, 05(08), 506–512. doi: 10.4236/epe.2013.58055

Mwakaje AG. 2008. Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. Renewable and Sustainable Energy Reviews, 12(8), 2240–2252. doi: 10.1016/j.rser.2007.04.013

Mwirigi J, Babulo B, Mugisha J, Walekhwa P, Melamu R, Nakami S, Makenzi P. 2014. ScienceDirect Socio-economic hurdles to widespread adoption of small-scale

biogas digesters in Sub-Saharan Africa : A review. Biomass and Bioenergy, 70, 17–25. doi: 10.1016/j.biombioe.2014.02.018
Mwirigi J, Balana BB, Mugisha J, Walekhwa P, Melamu R, Nakami S, Makenzi P. 2014a. Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: A review. Biomass and Bioenergy, 70, 17–25. doi: 10.1016/j.biombioe.2014.02.018
Mwirigi J, Balana BB, Mugisha J, Walekhwa P, Melamu R, Nakami S, Makenzi P. 2014b. Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: A review. Biomass and Bioenergy, 70, 17–25. doi: 10.1016/j.biombioe.2014.02.018
Mwirigi JW, Makenzi PM, Ochola WO. 2009. Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. Energy for Sustainable Development, 13(2), 106–115. doi: 10.1016/j.esd.2009.05.002
Nevzorova T, Kutcherov V. 2019. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. Energy Strategy Reviews, 26, 100414. doi: 10.1016/j.esr.2019.100414
Ohimain EI. 2013. A review of the Nigerian biofuel policy and incentives. Renewable and Sustainable Energy Reviews, 22, 246–256. doi: 10.1016/j.rser.2013.01.037.
Okello C, Pindozzi S, Faugno S, Boccia L. 2013. Development of bioenergy technologies in Uganda: A review of progress. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2012.10.004.
Omer AM. 2005. Biomass energy potential and future prospect in Sudan. Renewable and Sustainable Energy Reviews,

9(1), 1–27. doi: 10.1016/j.rser.2003.12.011
Orskov ER, Yongabi AK, Subedi M, Smith J. 2014. Overview of holistic application of biogas for small scale farmers in Sub-Saharan Africa. Biomass and Bioenergy, 70, 4–16. doi: 10.1016/j.biombioe.2014.02.028.
Osei-Marfo M, Awuah E, de Vries NK. 2018. Biogas technology diffusion and shortfalls in the central and greater Accra regions of Ghana. Water Practice and Technology, 13(4), 932–946. doi: 10.2166/wpt.2018.100.
Painuly J, Fenhann JV. 2002. Implementation of Renewable Energy Technologies: Opportunities and Barriers: Summary of Country Studies. In Institute of Technology.
Parawira W. 2009. Biogas technology in sub-Saharan Africa: status, prospects and constraints. Reviews in Environmental Science and Bio/Technology, 8(2), 187–200. doi: 10.1007/s11157-009-9148-0
Pollmann O, Podruzsik S, Fehér O. 2014. Social acceptance of renewable energy: Some examples from Europe and developing Africa. Society and Economy, 36(2), 217–231. doi: 10.1556/SocEc.36.2014.2.5
Rahman MS, Majumder MK, Sujan MHK. 2021. Adoption determinants of biogas and its impact on poverty in Bangladesh. Energy Reports, 7, 5026–5033. doi: 10.1016/j.egyr.2021.08.027
Rasimphi T, Tinarwo D. 2020. Relevance of biogas technology to Vhembe district of the Limpopo province in South Africa. Biotechnology Reports, 25, e00412. doi: 10.1016/j.btre.2019.e00412
Rastogi N. 2016. Pestle technique – A tool to identify external risks in construction projects. 384–388.
Roopnarain A, Adeleke R. 2017a. Current status, hurdles and

future prospects of biogas digestion technology in Africa. Renewable and Sustainable Energy Reviews, 67, 1162–1179. doi: 10.1016/j.rser.2016.09.087

Roopnarain A, Adeleke R. 2017b. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renewable and Sustainable Energy Reviews, 67, 1162–1179. doi: 10.1016/j.rser.2016.09.087

Ruane J, Sonnino A, Agostini A. 2010. Bioenergy and the potential contribution of agricultural biotechnologies in developing countries. In Biomass and Bioenergy. doi: 10.1016/j.biombioe.2010.04.011

Rupf GV, Bahri PA, De Boer K, McHenry MP. 2015. Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. In Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2015.07.107

Rupf GV, Bahri PA, De Boer K, McHenry MP. 2016. Broadening the potential of biogas in Sub-Saharan Africa: An assessment of feasible technologies and feedstocks. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2016.04.023

Sarakikya H. 2015. Renewable Energy Policies and Practice in Tanzania: Their Contribution to Tanzania Economy and Poverty Alleviation. International Journal of Energy and Power Engineering, 4(6), 333. doi: 10.11648/j.ijepe.20150406.12

SE4All. 2013. Etude diagnostique du secteur de l’Energie au Burundi dans le cadre de l’Initiative du Secrétaire Général des Nations Unies sur l’Energie durable pour tous (Sustainable Energy for All).

Shane A, Gheewala SH, Fungtammasan B, Silalertruksa T, Bonnet S, Phiri S. 2016. Bioenergy resource assessment for Zambia. Renewable and Sustainable Energy Reviews, 53, 93–104. doi: 10.1016/j.rser.2015.08.045

Shane A, Gheewala SH, Phiri S. 2017. Rural domestic biogas supply model for Zambia. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2017.05.008

Smith JU, Fischer A, Hallett PD, Homans HY, Smith P, Abdul-Salam Y, Emmerling HH, Phimister E. 2015. Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2015.04.071

SNV. 2018. Technical potential for household biodigesters in Africa. 1–6.

So D, Oo F, Eo Y. 2020. Bioenergy technologies adoption in Africa: A review of past and current status. Journal of Cleaner Production, 264, 121683. doi: 10.1016/j.jclepro.2020.121683

Surendra KC, Takara D, Hashimoto AG, Khanal SK. 2014. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2013.12.015

Surroop D, Bundhoo ZMA, Raghoo P. 2019. Waste to energy through biogas to improve energy security and to transform Africa's energy landscape. In Current Opinion in Green and Sustainable Chemistry. doi: 10.1016/j.cogsc.2019.02.010

Tangka J, Ketuma C, Ajaga N, Viyoi C. 2016. Modelling of the Operation of a Small Generator Set Powered by Scrubbed Biogas from Cow Dung. British Journal of Applied Science

& Technology, 14(1), 1--8. doi: 10.9734/bjast/2016/22903
Terrapon-Pfaff J, Gröne MC, Dienst C, Ortiz W. 2018. Productive use of energy – Pathway to development? Reviewing the outcomes and impacts of small-scale energy projects in the global south. Renewable and Sustainable Energy Reviews, 96 (October 2017), 198–209. doi: 10.1016/j.rser.2018.07.016
UNDP Regional Bureau for Africa (RBA), UR. 2018. Transforming lives through renewable energy access in Africa UNDP's Contributions: UNDP Regional Bureau for Africa (RBA). UNDP Africa Policy Brief Vol. 1, No. 1, 1(1).
United Nations. 2015. The Millennium Development Goals Report. United Nations, 72. doi: 978-92-1-101320-7
United Nations Economic Commission for Africa (UNECA) (2018. Achieving SDG 7 in Africa. United Nations, Department of Economic an Social Affairs.
Valentinuzzi F, Cavani L, Porfido C, Terzano R, Pii Y, Cesco S, Marzadori C, Mimmo T. 2020. The fertilising potential of manure-based biogas fermentation residues: pelleted vs. liquid digestate. Heliyon, 6(2). doi: 10.1016/j.heliyon.2020.e03325
Venkata RP, Michael T, Sumi M, Kammila S. 2015. The State of the Global Clean and Improved Cooking Sector. ESMAP and GACC. doi: 007/15
Verbist B. 2018. Development of a viable domestic biogas sector : Challenges and successes in Africa.
Walekhwa PN, Mugisha J, Drake L. 2009. Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. Energy Policy, 37(7), 2754–2762. doi: 10.1016/j.enpol.2009.03.018.

Walwyn DR, Brent AC. 2015. Renewable energy gathers steam in South Africa. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2014.08.049

Wassie YT, Adaramola MS. 2019. Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. In Renewable and Sustainable Energy Reviews. doi: 10.1016/j.rser.2019.05.037.

Wilson L. 2007. Promoting biogas systems in kenya: A Feasibility Study Biogas for Better Life An African Initiative. Analysis.

3. Economic viability and factors affecting farmers' willingness to pay for adopting small-scale biogas plants in rural areas of Cameroon

Adapted from Ketuama CT, Roubík H. 2024. Economic viability and factors affecting farmers' willingness to pay for adopting small-scale biogas plants in rural areas of Cameroon. Renewable Energy, 230, 120895. doi: 10.1016/j.renene.2024.120895.

Contributions:
Both authors conceived the idea for the paper. Chama Theodore Ketuama collected, analyzed the data and wrote the original manuscript. Revisions were done by Chama Theodore Ketuama and Hynek Roubík. Supervision was done by Hynek Roubík.

Abstract
This study provides an in-depth economic analysis to aid decision-making in the adoption of small-scale biogas technology in rural areas of Cameroon. It also provides evidence of the field investment characteristics of the biogas energy supply in rural areas of Cameroon. The methodology focused on assessing the economic viability of the different sizes of biogas plants and the willingness of farmers to pay for the same. A sample of 180 farmers was selected for the study. Data collection was carried out from December 2020 to May 2021 using a questionnaire survey and participant observation. The results show that all small-scale biogas plants are economically viable. Benefit-cost ratios were 1.01, 1.19, 1.50, 1.02, 1.21 and 2.04 for the $4m^3$, $6m^3$, $8m^3$, $10m^3$, $20m^3$, and $25m^3$ biogas plants. The net present values in US dollars (USD) were 959, 1790, 2695, 2658, 6047, and 12267 for the $4m^3$, 6

m^3, $8m^3$, $10m^3$, $20m^3$, and $25m^3$ biogas plants respectively. The internal rates of return were higher than the applied discount rate of 12%. The minimum payback period of 2.24 years was recorded for the $25m^3$ while the maximum of 3.37 years was recorded for the $10m^3$ biogas plants respectively. With a disproportionate increase in the cost of biogas plants by 20% and a 20% decrease in benefits with a discount factor, the net returns are positive, indicating that all the biogas plants are economically viable. The mean willingness to pay is estimated at 13 USD or 8000 FCFA. This resulted in an average repayment period of 11.5 years. The provision of extension services, financial incentives, and regulation of the small-scale biogas market will motivate farmers to adopt the technology.

Keywords: Biogas; benefit-cost ratio; sensitivity analysis; willingness to pay; clean energy; Cameroon.

3.1. Introduction

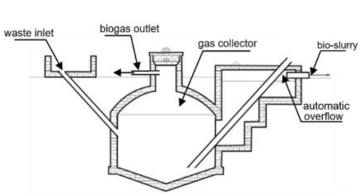
Enabling access to modern energy services in resource-poor countries continues to be relevant to achieving development objectives such as poverty reduction, access to drinking water, improvement of health and education, greater socio-economic role for women, and greater agricultural production (Rubinstein et al. 2021). Biogas is considered as an environmentally friendly alternative to unsustainable energy sources such as fuelwood and charcoal (IRENA 2017). Biogas technology in Africa needs a revolution to achieve a modern energy transition (Kalina et al. 2022). The possible alignment relies partly on improving both the economic viability and farmers' willingness to pay (WTP) for the biogas plants. In recent decades, biogas technology in Sub-Saharan Africa (SSA) has witnessed the failure of hundreds or even thousands of biogas projects, limiting access to modern energy (Ketuama et al. 2022). Failed biogas projects have been reported in Uganda (Kalina et al. 2022), Tanzania (Hewitt et al. 2022) and Senegal (Diouf & Miezan 2019). The failure of these biogas plants has been attributed partly to poor construction and installation, sub-standard feeding practices, operation and maintenance issues, and inadequate training and knowledge about the technology. Since 2020, Africa is facing the first recession in 25 years, which has affected the income from fossil fuel production, supply chains, and foreign direct investment patterns. This has affected access to modern energy in Africa, with the number of people without access to clean cooking fuels increasing to 970 million in 2021 (IEA 2022) against 917 million in 2019 (Opoku 2022). Cameroon is no exception. In 2021, 65.4% of the total population have access to electricity (IEA et al. 2023). In rural areas, only 24. 8% of the population had access to electricity, against 94.7% in the urban areas. Electricity from renewable sources excluding hydroelectricity serves only 1.1% of the population. The development of renewable energy in Cameroon is faced with several bottlenecks vis-à-vis the policies, regulations, institutions, knowledge diffusion, technical capabilities; and financial support (Muh et al. 2018).

Since the introduction of biogas technology in Cameroon in the second half of the twentieth century (the 70s) (Steedman, 1970), its adoption and diffusion has been very slow. The technical potential (exploited and unexploited) of small-scale biogas plants in Cameroon is estimated to range from 284,000 to 724,000 (SNV 2018). The 'technical potential' is defined as the number of households that can meet the two basic requirements – sufficient availability of both dung and water –

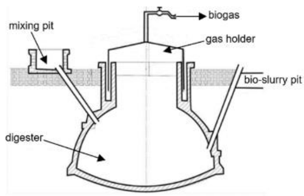
to operate a biogas plant. By 2018, only about 500 constructed biogas plants were reported in the country (Ndongsok et al. 2018), corresponding to an exploited technical potential of less than 1%. This has contributed to the persistent rural households' dependence on traditional energy sources such as fuelwood, charcoal, and dry dung for cooking. Approximately 94% of the households in rural areas of Cameroon still use fuelwood for cooking (Esong et al. 2021). The demand for fuelwood in Cameroon is, on average, 1kg/person/day (Atyi et al. 2016). Consequently, unwanted deforestation of the natural forest is continuing while women and children suffer other socio-economic setbacks due to fuelwood collection drudgery and use. The use of fuelwood also causes household air pollution (HAP) which is a risk factor for several diseases, such as respiratory diseases, cardiovascular disorders, adverse pregnancy outcomes and cataracts (Esong et al. 2021). Biogas technology responds at the local level to three dimensions of sustainable development; environmentally by reducing the side effects caused by the energy supply chain and inefficient energy use: greenhouse gas (GHG) emissions, air pollution and depletion of the natural resources; economically by reducing energy dependence and by enabling the activities that generate business and wealth, e.g. by increasing local business investment in renewable energy and energy efficiency; and socially by improving human health, creating jobs and involving the citizens in decision-making processes (Neves & Leal 2010). In rural areas of Cameroon, most of the farmers practice subsistence farming which combines agriculture and animal husbandry. With the increasing cost of inorganic fertilisers in the local markets (WFP 2022), digestate, a by-product of the biogas production process (anaerobic digestion) is a potential alternative that can contribute to reducing the farmers' cost of production. Biogas is also a source of skills enhancement and employment for rural areas (Parawira 2009). In refugee settlements in Africa and other parts of the world, biogas technology is used to provide clean cooking energy while improving sanitation (IRENA 2019).

Biogas technology relies on the process of anaerobic digestion to produce biogas. Anaerobic digestion has been identified as a renewable energy pathway for providing clean fuel to energy-deficient households around the world (IEA 2022). Anaerobic digestion is a chemical process that breaks down organic matter from plant and animal origin in the absence of oxygen to valuable biogas. Biogas is a mixture of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and other trace elements. Biogas constitutes approximately 50 – 70% methane and 30 – 50% carbon dioxide. Biogas produced in Cameroon has an acceptable quality for use in appliances such as biogas cookers and lamps (Ketuama et al. 2022). The mean calorific value of biogas is approximately 22 MJ/m^3. A biogas volume of 0.2 m^3 is equivalent to 1kg of fuelwood, 0.09 kg of liquefied petroleum gas (LPG), 0.13 litre of kerosene, 0.15ℓ of gasoline (petrol) and 0.13ℓ of diesel. The average biogas consumption range of 0.1 - 0.3 m^3/person per day (assuming one warm meal per day). The specific gravity of biogas with a composition of 60% methane and 40% CO_2 is 0.93 (Marchaim 1992). The production of biogas releases a by-product known as digestate (or bio-slurry). It consists of approximately 93% water and 7% dry matter, of which 4.5% is organic and 2.5% inorganic matter (Baltrėnas & Baltrėnaitė 2018). The hydraulic retention time (HRT) ranges between 20 to 50 days in Cameroon as well as in India (Singh & Sooch 2004) and China (Duan et al. 2014).

In rural areas of Cameroon, like in other developing countries, the most widely used designs of biogas plants are the fixed-dome (Figure 3.1a) and the floating drum (Figure 3.1b). The choice of the design depends on the performance of the biogas plant. These BGPs are constructed with different materials, including plastic, masonry (concrete/brick), steel and resin-reinforced fibreglass. Farmers use a variety of organic waste, including food waste, crop residues, animal dung and faecal sludge (septage), as feedstock for their BGPs. The predominantly used design of the BGPs in Cameroon is the masonry fixed-dome (often built under the ground to maximise space, increase structural stability and insulation). In Cameroon, a biogas plant of 8m^3 can meet the energy needs for cooking and lighting of most households (MINEE, 2010).



a) Fixed-dome design



b) Floating drum design

c) Fixed-dome BGP

d) Underground domestic BGP

Figure 3.1. Main designs of biogas plants in Cameroon

To mobilise the available biogas potential in rural areas of Cameroon, there is need for the efficient utilisation of the available resources owned by the farmers. As a result, the economic viability and willingness to pay become important considerations for implementing financially sustainable biogas projects with long-term ownership. The economic viability seeks to optimise the monetary surplus from utilising biogas and organic fertiliser against the capital investment cost. The economic viability analysis essentially determines whether the investment in biogas technology is profitable or not and the related financial risks. The economic viability assessments of small-scale biogas technology have been performed across the world to support decision-making to adopt and obtain optimal benefits from it. Some of the studies include in Uganda (Walekhwa et al. 2014), Bangladesh (Sarker et al. 2020), Ethiopia (Geddafa et al. 2023) and Pakistan (Abbas et al. 2017). Most of these studies showed that small-scale biogas technology is economically viable. However, it was revealed that the revenue from energy substitution was insufficient to cover the project cost without the revenue from bio-slurry and environmental benefits. As such, for every biogas project, the viability assessment is crucial to achieve best outcomes. Although biogas technology is economically viable at the household level, farmers have to be willing to pay for it, to enjoy the benefits. Farmers' WTP for biogas plants refers to the amount of money that they are willing to spend or invest in the technology. Knowledge of WTP enables the understanding how farmers perceive the value and social acceptance of biogas technology. One of the major barriers to domestic biogas technology in Sub-Saharan Africa is the lack of the financial capacity to pay for the capital investment cost (Ketuama et al.

2022). Consequently, the amount that most farmers are willing to pay has in most cases been far less than the market price of the biogas plants. This was evident in Nepal (Thapa et al. 2021), Uganda (Kabyanga et al. 2018), Madagascar (Andriamanohiarisoamanana et al. 2022) where assessments were conducted. These studies suggested that the provision of environmental income (via carbon credits), credit facilities, low-cost biogas plants, adult education and further promotion could lead to more rapid and widespread adoption.

Despite the application of the concepts of economic viability and WTP to inform farmer's decision to adopt small-scale biogas technology in different parts of the world, no formal studies have been conducted for the case of Cameroon. To this effect, the following research questions were formulated: Are small-scale biogas plants in rural Cameroon economically viable? Are farmers willing to pay for the biogas plants? This study aims to aid decision-making in investing and obtaining optimal benefits from small-scale biogas technology in rural areas of Cameroon. The economic viability was assessed though the cost-benefit analysis. Farmers' WTP and the influencing factors were assessed using contingent valuation and probit model. Data were collected from December 2020 to May 2021 in Cameroon using questionnaire survey and participant observation from 180 rural farmers, amongst which 45 owned operational biogas plants of sizes ranging from 4 m^3 to 25m^3. This study is limited to rural biogas plants and does not include the situation in peri-urban areas of the country. This study provides additional information to farmers, policymakers, and other investors on the economic viability and the factors that influence the willingness of farmers to pay for small-scale biogas technology in rural areas of Cameroon.

3.2. Methodology

3.2.1. Study area

This study was carried out across the five agroecological zones (AEZs) of Cameroon, as shown in Figure 3.2. Cameroon is located between latitude 1° and 13° North and longitude 8° and 17° East of the Greenwich meridian. The climatic conditions and vegetation make possible the production of crops and livestock-rearing activities as well as biogas production. Agriculture and animal husbandry are the main sources of livelihood for more than 60% of the rural population of Cameroon (GIZ 2020). The primary biogas feedstocks in rural areas of Cameroon are cow dung and other livestock manure (horses, pigs, donkey, poultry, goats, rabbits). A very small amount of food waste is used for biogas production in rural households.

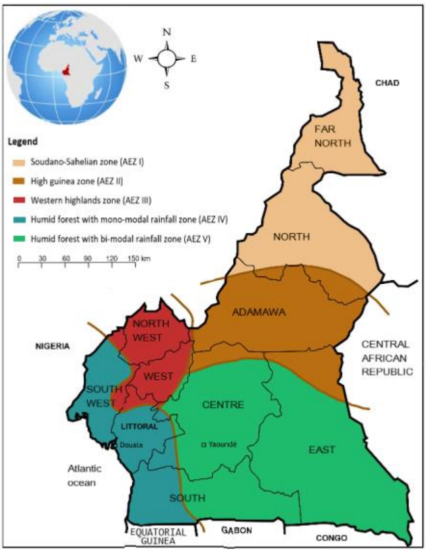


Figure 3.2. Map of Cameroon showing the different agroecological zones

3.2.2. Sampling technique and data collection

The study targeted farmers including users and non-users of biogas technology. Equation 3.1 (Taherdoost 2017) was used to determine the size of a representative sample of the farmers due to their dispersed settlements and owning very few biogas plants. Given that the technical potential of biogas plants in Cameroon ranges from 284,000 to 724,000, an average of 504,000 biogas plants was used to estimate the sample size for the survey.

$$n = \frac{p(100-p)z^2}{E^2} \quad \text{.................................} \quad (3.1)$$

where n is the required sample size, p is the percentage of the average technical potential (86.4%), z is the value corresponding to the confidence level of 95% (1.96), and E is the margin of error (±5%). Using this method, a sample of 180 farmers was required for this study. Multi-stage sampling approach was used to identify the farmers (respondents). The first stage involved quota sampling where 36 farmers were sought from each AEZ comprised of users (with functional biogas plants) and non-users of biogas technology. In the second stage, snowballing approach was used to search for biogas users. Once one biogas user was identified, this farmer provided information to aid the identification of the other user or users. Given that these biogas users were scarce, the quota was completed by randomly selecting farmers (non-biogas users). This approach enabled the identification of all the 180 farmers required for this study. Table 3.1 shows the distribution of the farmers for the different AEZs. Questionnaire surveys were administered to collect socio-economic and willingness to pay data from all the respondents. For biogas users, the questionnaire was used to collect additional data on the different costs (installation, labour and maintenance of the biogas plants) and revenues associated with the use of the biogas plants. Collecting data across the five AEZs aided in obtaining a sample whose results can be validated across the country. The biogas feedstock in AEZ I and II is dominantly cow dung, AEZ III has a higher variety of feedstocks including in addition to cow dung, poultry and plant residues, while AEZ IV and V uses mostly pig waste as biogas feedstock. All these feedstocks produce sufficient and similar quality for biogas for household cooking and lighting (Ketuama et al. 2022).

Table 3.1. Distribution of farmers

Location	**Administrative regions**	**Non-biogas users**	**Biogas users**
AEZ I	North and the Far North	33	3
AEZ II	Adamawa Region and the northern part of the Mbam Divisions (Centre Region) and Lom et Djerem (East Region)	20	16
AEZ III	West, Northwest Regions and parts of South West Region	27	9
AEZ IV	Littoral and South West Regions	31	5
AEZ V	Centre, East and South Regions	24	12
Sub-total		135	45
Total		180	

3.2.3. Data analysis

Data analysis was performed to determine: i) the economic viability of biogas plants using cost-benefit analysis and sensitivity analysis; ii) the willingness of farmers to pay using contingent valuation; and iii) the factors influencing farmers' willingness to pay for the BGPs using the probit regression model. The marginal effects were determined as an indication of how much the WTP (dependent variable) varies when each independent variable changes. Before the collected data were used for the analysis, they were cleaned, categorised and coded. The software used to perform the different calculations and statistical analysis were Microsoft Office Excel and the Stata software version 16.0.

3.2.4. Economic viability analysis

The cost-benefit analysis (CBA) was performed to determine the economic viability of small-scale biogas plants in rural areas of Cameroon. The CBA is an appropriate tool to assess the viability of biogas technology (Singh & Sooch 2004; Walekhwa et al. 2014; Kossmann et al. 1999). The benefit-cost ratio (BCR) as the key indicator for the viability assessment was estimated. Other related indicators estimated were the net present value (NPV), internal rate of return (IRR), and payback period (PBP).

Assessment of costs and benefits of biogas plants

The main costs associated with the biogas plant are the capital and installation costs, as well as operation and maintenance costs. These costs comprise all expenses for acquiring materials/equipment and installing the BGP and accessories. The costs of the biogas plants were estimated based on the observation of invoices used during the construction of the biogas plants. Where the invoices were not available, farmers were asked (recall method) about the cost of materials and labour they incurred during the construction of the biogas plants. Cost variation in the capital investment cost of the same size of biogas plant in different parts of the country due to variations in the cost of the construction materials, the design and size of the biogas plant, and the local labour or installation costs (depending on the bargaining power of the project owner). The materials used for the construction of the biogas plants susceptible to depreciation were masonry materials (bricks and concrete). The annual depreciation was assumed at 4% of the capital and installation costs (Walekhwa et al. 2014). The cost of land was excluded from the analysis because the households already owned land which was previously acquired with or without the intention of acquiring a biogas plant. However, adding the cost of land will evidently increase the capital investment cost and reduce the viability of the BGPs. The annual operation and maintenance (O&M) costs considered in this study were the costs of collecting feedstocks, maintenance and depreciation of the biogas plant. It is assumed that running a domestic biogas plant takes about an hour a day or a man-day of approximately 0.13, considering that a man-day is eight hours of work. The average annual maintenance cost is approximately 4% of the capital cost (Kandpal et al. 1991).

The benefits considered in the viability assessment are the annual monetary values (revenues) from the use of the biogas plants or technology as an alternative source of fuel and organic fertiliser. Fuel substitution benefits were assessed as the savings from the acquisition of the other previously consumed fuels, mainly fuelwood and kerosene. This included the expenditures incurred in the sourcing of fuelwood and kerosene (buying in some cases and transporting to the household). Fuelwood was used for cooking while kerosene was used for lighting. During the study period, fuelwood was either collected from the forested or bought in bundles of 10 to 40kg across the country. A fuelwood bundle of 32kg was used for approximately 6 days. The benefits from organic fertilisers were estimated by calculating the monetary equivalent of inorganic fertiliser that have been replaced with digestate from the biogas plant. For digestate, the values were estimated as the amount of money saved from substituting inorganic fertiliser with digestate. This amount varied from one farmer to the other. There is no standard market price of digestate in Cameroon. The average monetary values of the biogas plants were calculated by multiplying the daily estimated values (of biogas, digestate, and labour-saving) by 365 days to obtain the annual benefits.

Estimation of economic viability indicators

Key indicators to determine the economic viability of biogas plants include the benefit-cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and payback period (PBP). For each size of BGP, the benefit-cost ratio was estimated using equation 3.2.

$$\text{Benefit - Cost Ratio} = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}} \text{ ………………... } (3.2)$$

where B_t is the benefits in year t; C_t is the costs in year t; i is the interest rate of the project, n is the number of years that the BGP is expected to operate (i.e. lifespan of the biogas plant,

considered at 15 years). If the ratio is greater than one (i.e. B/C > 1), the biogas project is viable otherwise, (B/C < 1), reject the biogas project as it is not viable (FAO 1996).
Before estimating the BCR, the net present value (NPV) is first estimated as the sum of the future cash flows over 15 years (lifespan of the BGPs). A 15-year lifespan was selected for the biogas plants in Cameroon based on the farmer's experience on the lifespan of BGP and literature such as in Muh et al. (2018). A discount rate of 12% was selected according to Walekhwa et al. (2014), and Gupta and Ravindranath (1997), applicable to the evaluation of rural projects and an average in Cameroon. For the biogas project to be economically viable, the NPV is expected to be positive. Otherwise, it will not be a viable energy source to the farmer.

With a known NPV, the IRR was estimated for the different BGPs. The IRR is the discount rate at which the NPV equals to zero as shown in equation 3.3. If the IRR is greater than the interest rate, the biogas project is viable. On the contrary, if the IRR is less than the interest rate, the biogas project is not viable. In comparing project options, the higher the IRR, the more viable is the project.

$$0 = \text{NPV} = - C_0 + \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} \quad \text{.............................. (3.3)}$$

The PBP which is the number of years required to recover the investment cost of the biogas plant is estimated with equation 3.4.

$$\text{Payback period} = \frac{Cost\ of\ installation}{Annual\ profit} \quad \text{........................ (3.4)}$$

Sensitivity analysis

A sensitivity analysis was performed by changing each of the input factors (cost and benefits) at a time and determining the output (NPV and IRR). In the calculations, a 20% increase or fall in both the cost and benefit of each biogas plant is considered. Several factors affect the costs and benefits of BGP in Cameroon including the cost of construction materials, geographical location, availability of feedstock, inflation, and marketing of digestate. In Cameroon, the BGPs are constructed with different materials, including masonry, plastic and reinforced fibreglass. Having considered the masonry biogas plants in the cost estimations, the construction of the same BGP size with plastic and fibreglass materials can lead to a 20% reduction in the cost. Depending on the location of the BGP in the country, the construction cost could increase. Distant collection of feedstocks has contributed to increased cost of biogas production. Price volatility due to inflation could also increase or decrease the capital investment and production costs. The benefits from the BGPs are also affected in some cases by the availability of inputs (water and dung) and marketing of digestate.

3.3. Contingent valuation and probit regression of willingness to pay factors

The contingent valuation method was applied through direct questionnaire surveys of farmers to state their willingness to pay for domestic biogas plants. WTP is the maximum amount of money an individual would give up in exchange for all the benefits associated with an environmental resource or technology. A farmer's WTP is the farmer's surplus attached to the equivalent price change for substituting fuelwood (and related energy sources) and inorganic fertilisers with biogas technology. Despite the WTP methodological criticisms raised by Frey and Iselin (2017) as a bad idea to measure the value of nonmarket items (or goods), the method is still relevant. Contingent valuation elicitation was done in three steps; i) presenting the technology to each farmer and asking if the farmer would be willing to pay for it; and ii) asking how much the farmer is willing to pay for the technology by presenting the different random bids. In practice, the elicitation was done as follows:

'To *produce biogas with the 8 m^3 biogas plant, enough for a household of 5 to 7 members, an estimated 60 to 80 kg of organic waste per day is required. This requires approximately 5 mature cows or 600 poultry fowls or 50 pigs and 60 to 80 litres of water´.*

While presenting the operation of the BGP to the farmer using photos, it was explained that the organic waste is mixed with water before feeding into the biogas plant.

'If a BGP that can adequately substitute fuelwood and other cooking fuels and provide you with organic fertiliser is installed at your home, would you be willing to use it? Would you be willing to pay for it? If yes, how much would you be willing to pay (random bids' corresponding values in FCFA presented) every month for it, considering that the estimated cost of the biogas plant and appliances is 1121400 FCFA (1800 USD)?´

To acquire a biogas plant in Cameroon, farmers usually save for months or even years in economic interest groups or financial institutions (microfinance and banks). A number of farmers, i responded 'yes' to the CV question if their true WTP was equal or higher than the random bids presented to them, otherwise their responses were 'no'. The responses were represented as a dummy variable y_i that took the value of 1 if a farmer responded 'yes' and 0 otherwise, as shown in equation 3.5.

$$y_i = \begin{cases} 1\ if\ WTP_i \geq B_i \\ 0\ if\ WTP_i < B_i \end{cases} \text{ .... } (3.5)$$

where WTP_i is farmer i's unobservable true WTP and B_i is the random bid presented to each farmer (as shown in Table 3.6). The bids were determined in relation with the monthly average cost of cooking energy per household, which was between USD 1.6 and 28.8.

To assess the factors influencing farmers' WTP, a representative model using the linear function as shown in equation 3.6 is used.

$$WTP_i = \mu X_i + \varepsilon_i, \ i = 1, 2, 3, \ldots\ldots, n \quad (3.6)$$

where μ is a vector of parameters, X_i is a vector of independent variables, and ε_i is an error term. The probability of getting the 'yes' responses given the independent variables which affected WTP_i (Pr (y_i = 1| X_i) is the probability that the unobservable WTP of each farmer (WTP_i) is more or equal to the bid offered to the farmer (B_i) and can be expressed as in equation 3.7:

$$P_i = (y_i = 1|X_i) = Pr(WTP_i \geq B_i) = Prob(\mu X_i + \varepsilon_i \geq B_i) \quad (3.7)$$

where B_i was the bid presented to farmer i. X_i represents the independent variables that were considered to affect y_i.

The probit model was appropriately used to estimate the probability of getting 'yes' responses from farmers, and it depended on the random bids offered and other independent variables, as shown in equation 3.8.

$$y_i = \beta_0 + \beta_1 B_i + \beta_2 X_{1i} + \beta_3 X_{2i} + \ldots + \beta_k X_{k-1)i} + \varepsilon_i \ldots\ldots\ldots (3.8)$$

where $X_{1,} \ldots, X_{k-1)i}$ are the selected independent variables that affect y_i. These variables are presented in Table 3.2. The coefficients β_0 and β_i are measures of the changes in ratio of the probabilities, also known as the odds ratio. Three levels of significance of 90%, 95% and 99% (or α=0.1, α=0.05, and α=0.01) of the model were analysed using the Stata software. According to Sun et al. (2014), the factors that predominantly affect household willingness to pay for domestic biogas plants as a substitute for biomass energy for cooking and lighting include socioeconomic factors such as household income, household energy cost, land ownership, and livestock practices (Sun et al. 2014). Apart from the latter factors, the availability of raw materials, financial/non-financial incentives, and awareness campaigns about the benefits of biogas technology, technical factors, political commitment, and institutional framework usually play a significant role in the sustainable adoption and development of biogas energy technology in rural areas (Nkunzimana et al. 2013). The mean willingness to pay (WTP_m) was calculated using equation 3.9.

$$WTP_m = -(\hat{\beta}_0 + \hat{\beta}_2 \bar{X}_{1i} + \hat{\beta}_3 \bar{X}_{2i} + \cdots + \hat{\beta}_k \bar{X}_{(k-1)i}) / \hat{\beta}_1 \ldots\ldots\ldots (3.9)$$

Table 3.2. Variables used in the probit model for assessing the factors influencing farmer's willingness to pay for biogas plant

Variable	Description	Measurement	Expected sign
X_1	Bid offered by farmer (USD)	Continuous	-
X_2	Educational level (number of years)	Continuous	±
X_3	Number of persons in farmer's household (number)	Continuous	+
X_4	Total farmland owned (ha)	Continuous	+
X_5	Expenditure on other energy sources that can be substituted with biogas (USD)	Continuous	+
X_6	Farmer's annual income (USD)	Continuous	+
X_7	Sufficient feedstock to operate a biogas plant (1 = yes; 0 = otherwise)	Binary	+
X_8	Water availability (1 = yes; 0 = otherwise)	Binary	+
X_9	Access to subsidies, loans and credits (1 = yes; 0 = otherwise)	Binary	+

Note: A positive sign indicates that an increase in the independent variable leads to an increase in the probability to get the 'yes' response. However, a negative sign indicates that an increase in the independent variable leads to a decrease in the probability of getting the 'yes' response. Note: 1 USD = 623 FCFA.

3.4. Results and discussion

3.4.1. Descriptive statistics

A total of 45 functional biogas plants were identified and distributed according to the sizes of the biogas plants of 4m^3 (9%), 6m^3 (11%), 8m^3 (51%), 10m^3 (16%), 20m^3 (11%) and 25m^3 (2%) respectively. The biogas plants were the fixed-dome (n = 42) and the floating drum (n = 3) designs respectively. The total volumetric capacities of these biogas plants ranged from 4m^3 to 25m^3. The average age of the farmers was 36 years, with minimum and maximum ages being 19 and 79 years, respectively. The gender distribution of the respondents was 118 (66%) males and 62 (34%) females. The educational distribution of the respondents showed that 102 (57%) had no formal education, 56 (31%) had primary education, 19 (11%) had secondary education and 3 (2%) had tertiary education. The average household size was 6 members (±1). Land ownership by farmers was assessed as the total of residential and farmland and having a sufficient area for the construction of the BGP. The number of farmers who owned sufficient land to construct a BGP was 164 (91%), while farmers who did not own land sufficient for the construction of the BGP was 16 (19%). The average land size owned by each farmer was 3 ha while the maximum size was 28 ha. The monthly expenditure by a farmer to provide energy for cooking and lighting for the household ranged from a minimum of 1.6 USD to a maximum of 28.8 USD; meanwhile, the average expenditure was 3 USD. The annual incomes of the farmers from agriculture and livestock activities ranged from 144 to 24000 USD, with an average of 1809 USD. When asked if the farmers were going to be able to have sufficient feedstock from livestock and agricultural activities for the operation of the 8m^3 biogas plant, 109 (61%) declared that were able to provide, while 71 (39%) could not. Given that the feedstock is mixed at a ratio of 1:1 with water before feeding into the BGP, 144 (80%) of the farmers declared that they were able to access water, while 36 (20%) declared that they did not have access to water to feed the biogas plant. With regards to subsidies, loans and credits, most of the farmers (94%) did not have access. Only as little as 6% had access. The farmers who had access, benefited from the National Biogas Programme (NBP) that was implemented from 2010 to 2014, other government projects and non-governmental organisations (NGOs). During the NBP, selected farmers were provided with subsidies up to 30% of the total cost of BGP to reduce the initial investment cost (Walekhwa et al. 2014). In most developing countries, subsidies have motivated farmers to adopt biogas technology (Sun et al. 2014; Ashma 2019). The micro-finance institutions (MFI) and banks do not yet have frameworks to provide loans to farmers to fund biogas projects. As promised during the NBP, the credit framework has not been developed, and so it is not operational in financial institutions. The bid amounts varied from a minimum of 8 USD to a maximum of 160 USD. The descriptive statistics are summarised in Table 3.3.

3.4.2. Cost of small-scale biogas plants in Cameroon

The construction costs vary with the size of the biogas plant. The average installation or fixed cost of the biogas plant was estimated at 900 USD for the $4m^3$ BGP and up to 6000 USD for the 25 m^3 BGP. In addition to the size of the biogas plant, the distance from the source of construction materials contributed to the variation in the cost of the biogas plants. Biogas plants in the northern part of the country (AEZ I and II)

Table 3.3. Descriptive statistics of variables used in probit regression

Variable	Mean value	Stand. Dev.	Min.	Max.
Bid offered by farmer (USD)	10.44	18.02	8	160
Educational level (number of years)	8.61	4.67	0	22
Number of persons in farmer's household (number)	5.82	2.87	1	17
Total farmland owned (ha)	3.07	3.43	0	28.80
Expenditure on other energy sources that can be substituted with biogas (USD)	3.03	2.93	1.6	28.8
Farmer's annual income (USD)	2007.84	2604.92	144	28800
Sufficient feedstock to operate a biogas plant (1 = yes; 0 = otherwise)	0.91	0.28	0	1
Water availability (1 = yes; 0 = otherwise)	0.90	0.29	0	1
Access to subsidies, loans and credits (1 = yes; 0 = otherwise)	0.05	0.23	0	1

Note: Min. = Minimum, Max. = Maximum

were more expensive than in the southern part due to the difficulty to access the construction materials. The average cost of 8m^3 biogas plant in Cameroon (1800 USD) was higher than in other countries such as 1130 USD in Uganda (Walekhwa et al. 2014), 641 USD in Bangladesh (Sarker et al. 2020), and 689 USD in Ethiopia (Geddafa et al. 2023). According to the farmers, the high labour costs contributed to the high installation cost. Approximately 70% of the biogas plants were fully funded by the farmers. The costs of the other 30% of the BGPs were offset by subsidies from the government and civil society. The annual operation and maintenance cost was estimated as 4% of the initial investment cost. So, the O&M cost increased from 36 USD for the 4m^3 BGP to 240 USD for the 25m^3 BGP.

3.4.3. Benefits of small-scale biogas plants in Cameroon

The survey showed that farmers obtained several socio-economic benefits from the use of their biogas plants. The use of biogas led to smoke reduction in all the farmers' households. These farmers revealed that they have less eye problems due to the reduction in smoke. An estimated 91% of the farmers reported that sanitation improved in their homes and the surroundings. Biogas technology enabled 67% of the farmers to save more money to pay for the education of their household members. Biogas consumption led to timesaving of an average of 9 hours per week initially spent on fetching fuelwood and other energy sources for their households. These farmers revealed that the extra time was spent to engage in more farming activities, carrying out house chores and other social activities such as attending community meetings and leisure. The economic benefits included an increase in the income of the biogas user households. The monetary benefits from the use of the biogas plants include savings from fuel consumption and the equivalent cost of inorganic fertilisers replaced with digestate. The average annual monetary benefits from fuel substitution amounted from 120 USD for the 4m^3 and up to 1080 USD for the 25m^3 biogas plants. The reduction in fuelwood consumption by the farmers' households is directly related to the reduction in anthropogenic pressure on the forests. This provides environmental benefits from the use of biogas technology.

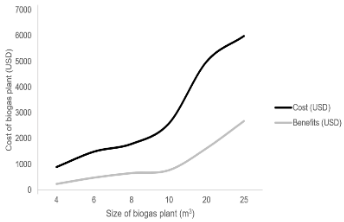
Farmers applied both liquid and dried digestate to their farms. Biogas users were also able to significantly replace (an average of 70%) the amount of inorganic fertiliser used on their farms with digestate. A total of 41 (91%) out of the 45 farmers revealed that the amount of digestate they produced did not meet the fertiliser needs of their farm. These were mostly the owners of the $4m^3$ to $10m^3$ biogas plants. For the $20m^3$, $25m^3$ and some of the $10m^3$ biogas plants, digestate was highly wasted due to the perception that digestate has a lower quality than the inorganic fertiliser. So, the digestate was usually given to other farmers for free, with very little sold at an average price of 4.1 USD per 50kg bag of dry digestate. When the farmers were asked about the marketing of the digestate, they revealed that it is not well known and accepted by farmers. Only one farmer sold liquid digestate at a price of 2.4 USD per 5 litres. The sale of digestate will increase the revenue from the biogas plants, thereby optimising the benefits from it. Digestate increased crop revenues by an average of 25 percent (Warnars 2012; Warnars & Hivos 2014). However, it is recommended to apply the digestate at a rate of 10 to 20 tons/ha in irrigated areas and 5 tons/ha in dry farming to have a significant increase in yields.

Table 3.4. Economics of small-scale biogas plants in rural areas of Cameroon in 2021

Indicator	Size of BGP (m^3)					
	4	**6**	**8**	**10**	**20**	**25**
1. Costs of the biogas plants (USD)						
Total construction cost	900	1500	1800	2600	5000	6000
Annual operation and maintenance cost (A)	36	60	72	104	200	240
2. Annual revenue from the biogas plants (USD)						
Fuel substitution	202	362	472	608	986	1752
Inorganic fertiliser substitution	107	181	260	268	836	1170
Total annual revenue (B)	309	543	732	876	1822	2922
Net annual revenue (B-A)	273	483	660	772	1622	2682
3. Other						
Net present value (USD)	959	1790	2695	2658	6047	12267
Benefit-cost ratio	1.01	1.19	1.50	1.02	1.21	2.04
Internal rate of return (%)	25	32	36	29	32	45
Payback period (years)	3.30	3.11	2.73	3.37	3.08	2.24

3.4.4. Economic viability of small-scale biogas plants in Cameroon

The net present values in USD were 959, 1790, 2695, 2658, 6047, and 12267 for the 4m^3, 6 m^3, 8m^3, 10m^3, 20m^3, and 25m^3 biogas plants, respectively. That is, for every dollar invested, the returns increased from the 4m^3 to 25m^3 biogas plants. This indicates that the larger the size of a biogas plant, the higher its profitability. A representative relationship between the exponential transformation of the NPV and the sizes of the BGPs is shown in Figure 3.3. The estimated benefit-cost ratios for the different sizes of BGPs were greater than 1, indicating that biogas technology is a viable energy source for farmers. The payback period ranged from a minimum of 2.24 years for the 25m^3 BGPs to a maximum of 3.37 years for the 10m^3 BGPs. The 8m^3 BGPs had the lowest PBP for the BGPs lower than or equal to 10m^3. The internal return rate for all biogas plants was greater than the discount rate of 12%, indicating that the BGPs were economically viable. The most profitable biogas plant based on the IRR was the 25m^3 BGP (45%), and the least was the 4m^3 BGP (25%). The 8m^3 BGP still retained the highest IRR (36%) for the BGPs equal to or lower than 10m^3. While it is worth noting that the small-scale BGPs are economically viable in Cameroon, the viability is largely dependent on the availability of feedstock, water and the management of the biogas plant. The viability of biogas technology is affected by the daily gas production capacity, feedstock, retention time, location, cost of substitutes, storage capacity, subsidy, and construction materials (FAO 1996). Therefore, to sustain viable biogas projects, good production and advertising management practises are required.



a) Cost and benefits of BGPs b) NPV vs size of the BGPs

Figure 3.3. Economic viability of biogas plants

3.4.5. Sensitivity analysis results

The sensitivity analysis results at 12% discount rate show that the increase in costs leads to a proportionate decrease in the NPV for all the biogas plants and vice versa. The IRR also decreases, rendering the investment less profitable. On the contrary, an increase in benefits tends to increase NPV and IRR, and vice versa. In both cases, the NPV remains positive while the IRR is far above 12%, indicating that the BGPs will be more profitable with the reduction in the cost. In all cases, the 25m^3 biogas plant had the highest IRR, representing the most profitable biogas plant. The increase in cost without optimising the benefits from the biogas plants will reduce the IRR, leading to the non-profitability of the biogas plants.

Table 3.5. Changes in NPV and IRR due to 20% increase and decrease in costs and benefits of BGPs at a discount rate of 12%

Size of BGP (m^3)	**4**	**6**	**8**	**10**	**20**	**25**
a) 20% increase in cost						
NPV (USD)	779	1490	2335	2138	5047	11067
IRR (%)	21	26	30	24	26	37
b) 20% decrease in cost						
NPV (USD)	1139	2090	3055	3178	7047	13467
IRR (%)	32	40	36	37	32	45
c) 20% increase in benefits						
NPV (USD)	1333	2448	3594	3710	8257	15920
IRR (%)	31	38	44	35	39	54
d) 20% decrease in benefits						
NPV (USD)	591	1132	1796	1606	3838	8613
IRR (%)	20	25	29	23	25	35

3.4.6. Farmers' willingness to pay for biogas plants in Cameroon

The hypothetical farmers' WTP for the $8m^3$ biogas plants as a function of the bid amounts is shown in Table 3.6. Of the 180 respondents, 63 (35%) respondents responded 'no' to the CV question and were therefore unwilling to pay for the BGP. The other 117 (65%) respondents had either already paid or were willing to pay for the BGPs and so responded 'yes' to the CV question. An estimated 36% of the farmers were willing to pay 8 USD per month (or annual contribution of 96 USD). This means that for the $8m^3$ BGP costing approximately 1800 USD (Table 3.4), 36% of farmers will take approximately 18.75 years to pay for it. Should an average repayment period of 3 years be considered, only 8% of the farmers are willing to pay the full cost of the BGPs.

The factors affecting the willingness of farmers to pay for the biogas plants are summarised in Table 3.7. The estimated variance inflation factor (VIF) showed that the values ranged from 1.03 to 2.33, with a mean of 1.36. This indicates that there is no multicollinearity in the independent variables of the model. Hence, all variables were accepted to determine the willingness to pay for the biogas plants.

Factors that had a very significant effect ($\alpha \leq 0.01$) on the WTP of the farmer for biogas plants in Cameroon were the bid amount, expenditure on other energy sources and the availability of subsidies, loans, and credits. The farmer's income and the availability of feedstock had significantly high effects ($\alpha \leq 0.05$) on the WTP of the farmer. Water availability had a significant effect ($\alpha \leq 0.1$) on farmer's WTP. Factors that did not show any significant effect on the farmer's WTP were the level of education, the size of farmer's household and

Table 3.6. Farmers' willingness to pay for hypothetical 8m^3 biogas plant

Component	Value										
Bid offered to farmer (USD)	0	8	16	32	48	64	80	96	112	128	160	Total
Number of farmers	63	64	31	12	3	1	1	2	1	1	1	180
Percentage (%)	35	36	17	7	2	1	1	1	1	1	1	100
Repayment duration (years)	0.0	18.8	9.4	4.7	3.1	2.3	1.9	1.6	1.3	1.2	0.9	

Table 3.7. Factors affecting farmer's willingness to pay for biogas plants in rural areas of Cameroon

Variable	**Coefficient**	**Stand. Error**	**VIF**	**Marginal effect**
Bid offered by farmer	- 0.0094***	0.001	1.23	- 0.086
Educational level	0.3786	0.364	1.12	0.016
Number of people in farmer's household	0.3275	0.005	1.08	0.013
Total farmland owned	- 0.8535	0.005	1.36	- 0.041
Expenditure on other energy sources that can be substituted with biogas	0.0027***	0.009	1.95	0.310
Farmer's annual income	0.0730**	0.000	2.33	0.160
Sufficient feedstock to operate a biogas plant	0.1422**	0.037	1.08	0.240
Water availability	0.0698*	0.041	1.03	0.014
Access to subsidies, loans and credits	0.0140***	0.072	1.04	0.088
Constant	0.4212	0.093	-	-

N = 180; Log likelihood = -10.1517134; LR χ^2 (9) = 14.39; Pseudo R^2 = 0.6334. * 10% significance level; ** 5% significance level; *** 1% significance level.

the land owned by the farmer. The bid amount was a hypothetical variable that was used to assess how farmer's purchasing power influences WTP for the BGPs. It was negative and had a highly significant effect. This means that the higher the bid amount is proposed, the probability that a farmer will not be willing to pay for the BGP is 0.08. This explains why the higher the farmer's income, the probability of WTP increases by 0.05. In comparison with the farmer's income, the expenditure on energy needed by the farmer exerts a higher influence on farmer and has the probability to increase WTP is 0.30. To the farmers, investing in biogas technology could help reduce or eliminate the expenditure on other energy sources. Farmers who received subsidies to construct their BGPs testified that the construction burden was reduced, thereby increasing the willingness to pay their share of the construction or investment cost. During the National Biogas Programme which lasted from 2010 to 2014, the farmers were provided with a subsidy of 30% of the initial investment cost to construct their BGPs (MINEE 2010). To other farmers, if they can have access to loans and credit, they would be willing to adopt the BGPs. This was justified by the positive and highly significant effect that subsidies, loans, and credit had on the farmer's WTP. As such, the increase in subsidies has a probability to increase WTP by 0.08. Subsidies also tend to reduce the payback period of the biogas technology (per the farmers investment cost recovery). Regarding feedstock, farmers who could access it enough to run the $8m^3$ biogas plant were more willing to pay. This can be justified by the positive and highly significant effect of feedstock availability on WTP. Feedstock availability has the probability to increase WTP by 0.24. Water availability, which is a prerequisite to run the BGP, showed a positive and significant effect on WTP. The more water is available for biogas production, the probability of a farmer's WTP increases by 0.01. For the rural BGPs, the feedstock-water ratio is usually 1:1.

Factors that did not show a significant effect but had a positive effect on farmer's WTP (and their probability levels) are educational level (p=0.016) and household size (p=0.013). Land ownership showed a negative and non-significant effect on farmer's WTP. An increase in land ownership has the probability to reduce farmer's WTP by 0.041. The construction of the biogas plant requires at least a land area of 30m^2 for the 8m^3 BGP. The mean willingness to pay was estimated at 13 USD or 8000 FCFA. This is almost 4 times less than the monthly amount required to repay the biogas plant in 3 years. On average, it will take approximately 11.5 years to pay for the BGP. Based on the bid distribution, it will take the farmers a minimum of 0.9 years (about 11 months) and a maximum of 18.75 years (about 18 years 10 months) to repay the BGP.

3.5. Conclusion and policy recommendations

3.5.1. Conclusion

This study first responded to the question of whether biogas technology is an economically viable clean energy option for rural households in Cameroon. The analysis shows that biogas technology is more viable as the size of the biogas plant increases. Based on the household energy demand, the 8m^3 biogas plants remain the most viable option for the farmers' households. The benefit-cost ratios ranged from 1.01 for the 4m^3 biogas plants to 2.04 for the 25m^3 biogas plants. The net present values were all positive, and the internal rate of returns were above the applied discount rate. The minimum and maximum payback periods were 2.24 and 3.37 years, respectively. Viability increased with the size of BGP. The farmers are not adequately engaged in the marketing of digestate and productive use of biogas, which tends to increase the payback period of the biogas plants. As such, the profitability of the technology is influenced by the management practices of each user. Farmers prefer biogas technology over traditional fuelwood and kerosene but based on the average amount they are willing to pay for the 8m^3 biogas plant, it will take 18.75 years to pay for the total cost. The distribution of the bid amounts shows that the farmers will take a minimum of 0.9 years (about 11 months) and a maximum of 18.75 years (about 18 years 10 months) to repay the full cost of the biogas plant.

3.5.2. Policy recommendations

Based on this study, some actions can be taken at the government level to make biogas technology more economically viable and attractive to farmers. Firstly, the country needs to enforce existing extension services to improve farmers' awareness about biogas technology, select the most appropriate biogas plants, valorise digestate, and engage in the productive use of biogas. Secondly, financial incentives in the form of tax exemptions or subsidies can be provided to farmers to offset the high capital investment cost. There is a need to assist financial institutions to offer low-interest loans to finance biogas projects. This would contribute to increasing farmers' willingness to pay for the biogas plants. Finally, government regulations are needed to persuade farmers to properly manage their waste through recycling to produce biogas and ensure that the private sector actors deliver standard biogas services to the farmers.

3.6. References

Abbas T, Ali G, Adil SA, Bashir MK, Kamran MA. 2017. Economic analysis of biogas adoption technology by rural farmers: the case of Faisalabad district in Pakistan. Renew Energy, 107:431–9. doi: 10.1016/j.renene.2017.01.060.

Andriamanohiarisoamanana FJ, Randrianantoandro TN, Ranaivoarisoa HF, Kono H, Yoshida G, Ihara I, Umetsu K. 2022. Integration of biogas technology into livestock farming: Study on farmers' willingness to pay for biodigesters in Madagascar. Biomass and Bioenergy 164, 106557.

Ashma V. 2019. Stakeholders' Perception About the Effectiveness of Renewable Energy Subsidy in Nepal: A Review of Biogas Subsidy. J. Inst. Eng. 15(3):375-384. doi:10.3126/jie.v15i3.32225

Atyi EA, Poufoun JN, Awono JPM, Manjeli AN, Kankeu RS. 2016. Economic and social importance of fuelwood in Cameroon. Int. For. Rev. 18(S1). doi: 10.1505/146554816819683735.

Baltrėnas P, Baltrėnaitė E. 2018. Small Bioreactors for Management of Biodegradable Waste. Springer. doi:10.1007/978-3-319-78211-9.

Diouf B, Miezan E. 2019. The Biogas Initiative in Developing Countries, from Technical Potential to Failure: The Case Study of Senegal. Renewable and Sustainable Energy Reviews, 101, 248–254. doi: 10.1016/j.rser.2018.11.011.

Duan N, Lin C, Wang P, Meng J, Chen H, Li X. 2014. Ecological analysis of a typical farm-scale biogas plant in

China. Front. Earth Sci. 8(3): 375–384. doi:10.1007/s11707-014-0411-5.

Esong MD, Ngnewa RSF, Guiagain MST, Agokeng BDK, Homla OTM, Pope D, Ateudjieu J. 2021. Distribution of sources of household air pollution: a cross-sectional study in Cameroon. BMC Public Health 21:318. doi:10.1186/s12889-021-10350-6.

FAO. 1996. Biogas technology. Biogas Technology: A Training Manual for Extension. Support for development of national biogas programme (FAO/TCP/NEP/4451-T). Nepal. Available from https://sswm.info/sites/default/files/reference_attachments/FAO%201996%20Biogas%20Technology%20A%20Training%20Manual%20for%20Extension.pdf. (accessed on 8 March 2023).

Frey BS, Iselin D. 2017. Economic ideas you should forget. In Economic Ideas You Should Forget. doi:10.1007/978-3-319-47458-8.

Geddafa T, Melka Y, Sime G. 2023. Cost-benefit Analysis and Financial Viability of Household Biogas Plant Investment in South Ethiopia. Sustainable Energy res. 10, 20. doi: 10.1186/s40807-023-00089-6.

GIZ. 2020. Green Innovation Centers for the Agricultural and Food Sector (ProCISA) Available from https://www.giz.de/en/downloads/giz2023-en-Cameroon-Factsheet-2020.pdf (accessed on 29 April 2024).

Gupta S, Ravindranath HN. 1997. Financial analysis of cooking Energy options for India. Energy Convers Manag 38(18):1869e76.

Hewitt J, Holden M, Robinson BL, Jewitt S, Clifford MJ. 2022. Not quite cooking on gas: Understanding biogas plant failure and abandonment in Northen Tanzania. Renewable Energy and Sustainable Energy Reviews, 165, 112600. doi: 10.1016/j.rser.2022.112600.

IEA (International Energy Agency). 2022. Africa Energy Outlook 2022. Available from https://iea.blob.core.windows.net/assets/220b2862-33a6-47bd-81e9-00e586f4d384/AfricaEnergyOutlook2022.pdf (accessed on 4 March 2023).

IEA, IRENA, UNSD, World Bank, WHO. 2023. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC. Available from https://data.worldbank.org/indicator/EG.ELC.RNWX.ZS?locations=CM (accessed on 28 April 2024).

IRENA (2017). Biogas for domestic cooking. Technology brief, International Renewable Energy Agency, Abu Dhabi.

IRENA. 2019. Renewables for refugee settlements: Sustainable energy access in humanitarian situations, International Renewable Energy Agency, Abu Dhabi.

Kabyanga M, Balana BB, Mugisha J. 2018. Are smallholder farmers willing to pay for a flexible balloon biogas digester? Evidence from a case study in Uganda. Energy for Sustainable Development 43, 23-129. doi: 10.1016/j.esd.2018.01.008.

Kalina M, Ogwang JÒ, Tilley E. 2022. From potential to practice: Rethinking Africa’s biogas revolution. Humanit. soc. sci. 9(1):374. doi:10.1057/s41599-022-01396-x

Kandpal C, Bharati J, Sinha CS. 1991. Economics of family-sized biogas plants in India. Energy Convers Manage 32(2):101e13.

Ketuama CT, Mazancová J, Roubík H. 2022. Assessment of biogas quality across rural household biogas plants in Cameroon. Proceedings of 22nd International Multidisciplinary Scientific GeoConference SGEM 2022. Vienna, Austria. doi:10.5593/sgem2022V/4.2/s18.04.

Ketuama CT, Mazancová J, Roubík H. 2022. Impact of market constraints on the development of small-scale biogas technology in Sub-Saharan Africa: a systematic review. Environ Sci Pollut Res 29:65978–65992. doi: 10.1007/s11356-022-22262-y.

Kossmann W, Habermehl S, Hoerz T, Kramer P, Klinger B, Wittur T, Klopotek FV, Krieg A, Euler H, Dornberger U. 1999. Biogas Digest Volume III Biogas – Costs and Benefits and Biogas – Programme Implementation. Information and Advisory Service and Appropriate Technology and GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit). https://www.pseau.org/outils/ouvrages/giz_biogas_digest_volume_iii_biogas_costs_and_benefits_and_biogas_programme_implementation_1999.pdf.

Marchaim U. 1992. Biogas processes for sustainable development. MIGAL Galilee Technological Centre Kiryat Shmona, Israel. Food and Agricultural Organization (FAO). Available from https://www.fao.org/3/t0541e/T0541E00.htm#Contents (accessed 12 April 2023).

MINEE (Ministry of Water Resources and Energy). 2010. National Biogas Programme. Blue Flame for Brighter Future for Cameroon.

Muh E, Amara S, Tabet F. 2018. Sustainable energy policies in Cameroon: A holistic overview. Renew. Sust. Energ. Rev. 82:3420–3429. doi:10.1016/j.rser.2017.10.049.

Ndongsok D, Mandeng T, Azemtsa H, Tankeu C, Ruppel CO. 2018. The state of biofuels development in Cameroon. Selected policy recommendations for sustainable biofuels production.

Neves AR, Leal V. 2010. Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework. Renew. Sust. Energ. Rev. 14(9):2723-2735. doi:10.1016/j.rser.2010.07.067.

Nkunzimana L, Huart M, Zaccai E. 2013. Toward policies for climate change mitigation: Barriers for family-sized biogas in the District of Gihanga, Burundi. Earths Future 2(5):245-255. doi:10.1002/2013EF000138.

Opoku FA. 2022. Achieving universal access to all forms of energy: A look at sub-Saharan Africa's penultimate goal. Available online on https://africa-energy-portal.org/blogs/achieving-universal-access-all-forms-energy-look-sub-saharan-africas-penultimate-goal (accessed on 18 January 2023).

Parawira W. 2009. Biogas technology in sub-Saharan Africa: status, prospects and constraints. Reviews in Rev. Environ. Sci. Biotechnol. 8(2):187–200. doi:10.1007/s11157-009-9148-0.

Rubinstein F, Betang E, Mbatchou B, Pope D, Puzzolo E. 2021. Transitioning to Modern Energy Cooking Services in Cameroon. A policy review of the energy sector. Department of Public Health, Policy and Systems, University of Liverpool.

Sarker SA, Wang S, Adnan KMM, Sattar MN. 2020. Economic feasibility and determinants of biogas technology adoption: Evidence from Bangladesh. Renewable and Sustainable Energy Reviews 123, 109766. doi: 10.1016/j.rser.2020.109766.

Singh KJ, Sooch SS. 2004. Comparative study of economics of different models of family size biogas plants for state of Punjab, India. Energy Convers. Manag. 45:1329–1341. doi: 10.1016/j.enconman.2003.09.018.

SNV. 2018. Technical potential for household biodigesters in Africa. Technical brief.

Steedman C. 1970. Cameroon Renewable Energy Project Possibilities. A report to the U.S. Agency for International Development identifying actions required to develop an assessment of Cameroon's energy needs. Ann Abor, Michigan. Contract No. Afr-C-1542. Project No. 698-0135. Available from https://pdf.usaid.gov/pdf_docs/PNAAH100.pdf (accessed 12 November 2022).

Sun D, Bai J, Qiu H, Cai Y. 2014. Impact of government subsidies on household biogas use in rural China. Energy Policy 73:748-756. doi:10.1016/j.enpol.2014.06.009.

Taherdoost H. 2017. Determining sample size; how to calculate survey sample size. International Journal of Economics and Management Systems. http://www.iaras.org/iaras/journals/ijems.

Thapa S, Morrison M, Parton K. 2021. Willingness to pay for domestic biogas plants and distributing carbon revenues to influence their purchase: A case study in Nepal. Energy Policy 158, 112521. doi: 10.1016/j.enpol.2021.112521.

Walekhwa PN, Lars D, Mugisha J. 2014. Economic viability of biogas energy production from family-sized digesters in Uganda. Biomass Bioenergy 70:26e39. doi: 10.1016/j.biombioe.2014.03.008.

Walekhwa PN, Mugisha J, Drake L. 2009. Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. Energy Policy, 37(7):2754–2762. doi: 10.1016/j.enpol.2009.03.018.

Warnars P. 2012. From biomass to biogas: present day status & future requirements. Master Thesis - International Development Studies, Utrecht University.

Warnars P., Hivos. 2014. Bioslurry: a supreme fertiliser - Positive effects of bioslurry on crops. Practitioners' Track, IFOAM Organic World Congress 2014, 'Building Organic Bridges', 13-15 Oct., Istanbul, Turkey.

WFP (World Food Programme). 2022. Food security analysis - Republic of Cameroon. Available from https://fscluster.org/sites/default/files/documents/2022.06_cmr_fertilizers.pdf (accessed on 26 April 2024).

4. Assessing the socio-economic and environmental impacts of small-scale biogas technology in rural areas of Cameroon using the Sustainable Livelihoods Framework

Adapted from: Balgah RA, Ketuama CT, Ngwabie MN, Roubík H. 2023. Africa's Energy Availability-Deficiency Paradox: Lessons from Small-scale Biogas Technology and Policy Implications. Environment, Development and Sustainability. doi: 10.1007/s10668-023-03810-z.

Contributions: RAB and CTK conceived the idea for the paper, analysed the data and identified relevant literature for the paper. RAB coordinated the field data collection. All the authors reviewed and contributed to the elaboration of the manuscript. Revisions were done by NMN, CTK, RAB and HR. Supervision was done by HR.

Abstract
The energy crisis associated with energy poverty in Cameroon continues to keep millions of men, women and children in absolute poverty due to inadequate access to clean energy. Despite its widely recognized importance for sustainable development, theoretical and policy discourses have largely remained dormant with respect to the role that the paradox of energy deficiency plays in the underdevelopment of Cameroon. This study illustrates how the exploitation of energy potential can be tailored to exert a positive impact on household livelihoods and sustainable development in Cameroon. Specifically, this study was aimed at determining the impact of biogas technology on the livelihood of beneficiaries in order to provide policy recommendations. The results show that the

beneficiaries' livelihood assets, including the human, physical, financial and social capital, were positively impacted by the use of biogas technology. The dominant impact of biogas technology was financial, as the beneficiaries witnessed a significant increase in their household incomes. This was possible through the reduction of the expenditure on fuelwood and the sale of digestate. The environmental benefits of disseminating biogas technology as a cleaner energy source were significant, providing evidence that mobilizing the biogas potential in Cameroon would lead to significant decarbonization of household energy supply. Integrating the livelihood enhancement components in energy interventions amid the enormous unexploited energy potential would contribute to the sustainable transformation of Cameroon.

Keywords: Energy; poverty; biogas; policy; sustainable development; Cameroon

4.1. Introduction

Energy access is crucial to achieving many, if not all the goals outlined in Agenda 2030 (Morrow 2018). As ascribed to the United Nations Environment Programme (UNEP 2017), the primary function of energy systems is to contribute to a better quality of life. Access to modern energy unlocks improved healthcare, education, economic opportunities, and even prolongs life. It is a significant constraint to social and economic development for those with limited or no access. Energy is essential for human existence and sustainable development. Despite the important role played by functional energy systems, energy resource-rich (high untapped potential) Africa will not achieve SDG7 in 2030 (African Union 2015).

The African Union (2063) rather plans to achieve the latter goal in 2063, that is, 33 years offset from the developed world. The paradox of Africa's renewable energy potential lies in the fact that, with the immense potential of renewable energy resources, utilization is still very low and insufficient to power the continent (Ogunniyi 2019). A key challenge for Africa to reduce its current energy deficiency lies in its weak capacity to harness, exploit, and use its rich stock of energy resources (UNEP 2017). Although drivers and barriers to energy access are country-specific, they are often strongly related to factors such as the levels of participation of different actors (including the private sector), political ambitions and priorities, availability of appropriate human capital and funding dependency, low rural markets, adaptation failure, and socio-political and environmental instability (Bonan et al. 2017). These barriers are surmountable, in as much as they are not natural, but are more likely to emanate from deficiencies in human capacity and other society-based processes.

4.2. Access to energy and poverty reduction in Cameroon

In 2015, the total electricity production for Cameroon was estimated at 628 ktoe with about 75% of it produced from hydroelectric sources. Also, in 2015 the electricity consumption was estimated at 526 ktoe, about 16% lower than production, with the industry consuming over 40% of the energy (UNEP 2017). Hydropower is likely the most dominant form of energy for over 25 million inhabitants in Cameroon. Its technically exploitable hydropower resources currently stand at 115000 GWh per year, making her the fourth largest potential producer of hydroelectricity in Africa. The installed capacity in

2020 is 792 MW, generating 5340 GWh (IHA 2020). The key hydroelectric power plants of Cameroon are Lagdo (72 MW), Edea (263 MW), and Songloulou (388 MW) (UNEP 2017), and Lom Pangar (30 MW). Hydroelectricity in Cameroon represents over 50% of the total available electricity.

Deforestation has become a disturbing issue in Cameroon, increasing at the rate of 220,000 ha per year from 1990 to 2015, not up to 2% of trees replanted each year. This probably provides evidence of a low level of commitment to promoting sustainable forest exploitation by companies involved in this sector in Cameroon (Oginni & Omojowo 2016). Biomass energy sources continue to be the primary option for heating and lighting for most of the poor living in agrarian areas in the country (Mboumboue & Njomo 2018).

Despite the availability and high potential for exploitation, solar energy, an important renewable energy source (RES); contributes only 0.01% of the installed electricity generation capacity in Cameroon (Kidmo et al. 2021). Solar irradiation in Cameroon varies between 4.00 kWh/m^2 d in Buea (South West Region) and 5.99 kWh/m^2 d in Maroua and Mora (Far North Region) (Kidmo et al. 2021). Despite the great potential for renewable energy, exploitation remains very weak. The wind energy sector is not well-known, and the country has no previous experience in wind power generation (Kidmo et al. 2021). Although access to power in Cameroon has steadily improved from 29% in 1991 to 62.66% in 2018 (World Bank 2021), there is still a big rural-urban divide. In 2018, the urban-rural access to electricity was 93% and 23%, respectively (IEA et al. 2020).

Perhaps the potential for increasing access to electricity in rural areas in Cameroon is at least theoretically favoured by the existing policy framework and institutions. Policies seek to attract investment and strengthen the national energy sector. This is thought to be possible through the exploitation of renewable energy potentials, especially hydroelectricity. The Ministry of Energy of Cameroon (MINEE) is the main public stakeholder promoting energy development initiatives. It defines and implements the government's energy policy. The *Agence de* Régulation du Secteur de l'Electricité (ARSEL) is the energy regulatory organ in Cameroon. Nevertheless, other actors are expected, especially in the renewable energy sector in rural areas. Civil society organisations also play a major role in promoting access to clean energy in Cameroon. It is in this light that HPI opted to increase the adoption of biogas technology in rural areas of Cameroon. This would also enable the reduction of poverty in the region. Therefore, we examine to what extent this project was able to achieve this ambitious objective among beneficiaries.

Currently, the preferred approach by Cameroon to addressing energy access has been through large-scale electricity grid rollout programmes. For people living in rural areas, often without a nearby grid, this approach is impractical and unsustainable in the long term. The future energy access of these areas depends on the promotion of small-scale or decentralised energy systems, including small-scale (household) biogas systems. Most past and current scholarships on energy in Africa have been focused on developing renewable energy sources (Hafner et al. 2018; Ouedraogo 2019) to meet the growing energy demand (Sanoh et al. 2014; Mukoro et al. 2022), climate change mitigation (Africa Progress Panel 2015; Abdelrazik et al. 2022) and the utmost goal of achieving African development goals (IEA 2022). As a complement to other studies, this study mainly aims to provide an energy supply approach that focuses on creating immediate positive impacts on the livelihood of households and sustainable development. This study specifically aims to i) determine the impact of biogas technology on the livelihood of users, and ii) estimate the environmental benefits of biogas technology as a cleaner alternative household energy. Evidence was gathered from an international intervention to promote biogas technology in Cameroon. Based on the findings, policy recommendations were proposed. These will be useful to energy policymakers in Cameroon striving to reduce energy poverty and deficiency amid high energy potentials.

4.3. Materials and methods

4.3.1. Background information of the Cameroon case study

The advent of the HPI in Cameroon focused on six out of the ten regions of the country (including the North West Regions). The project in general lasted for over 40 years, implementing grassroot integrated smallholder livestock and agricultural projects. The smallholder dairy development project stimulated the establishment of several zero-grazing dairy farms among rural farms in the North West Region creating a great opportunity for biogas production for domestic consumption. Biogas production was believed to reduce the anthropogenic pressure on forest resources predominantly used as a source of energy for rural farmers and improve the economy and welfare of these households and their communities (HPI 2015). To exploit the biogas potential, HPI initiated the biogas technology intervention in 2012, and it lasted till December 2013. This intervention would not only provide household energy but also improve waste management at the farms and provide organic fertilizer for crop production.

The North West Region is part of the Western Highlands of Cameroon. The Western Highlands is one of the major ecological zones in Cameroon (Innocent et al. 2016). Apart from playing host to the largest numbers of mountainous plants and animals, it consists of forest and grassland (Toh et al., 2018). Many predominantly rural households in the highlands rely on fuelwood for energy supply (Kimengsi et al. 2020). Fuelwood consumption in rural areas of these highlands is currently estimated at approximately 71,027 tons per year (Eba'a et al. 2016). The need for alternative energy is, therefore, obvious, considering that the need for energy has increased the level of deforestation in the region (UNEP 2017). With this in mind, HPI initiated as part of a project to promote the production and consumption of biogas as an alternative to fuelwood in selected households in the North West Region of Cameroon. The project's objective was to reduce energy deficiency and improve the livelihoods of beneficiaries through the promotion of domestic biogas technology. The pilot project directly targeted 800 resource-limited dairy cattle farming rural households in seven communities in North West Region of Cameroon. The target beneficiaries were dairy farmers who were all practicing the zero-grazing system.

4.3.2. Data collection

Data collection for this study began in 2015, as some of the impacts of the project could already be measured on the beneficiaries of the biogas project. The beneficiaries were the only target group because they were the first adopters of biogas technology in the region. So, there was no control group. Both qualitative and quantitative data were collected during on-site visits and face-to-face meetings with respondents. The variables are presented in Table 4.1. Data were collected through interview of beneficiaries, focus group discussions (FGD) and observations. The interview of each beneficiary lasted for 30 minutes. During each interview, data was collected with a pen and paper. Mostly quantitative data were recorded during this interview. One FGD each was organised for Santa Mbei and Santa Njong while another was organised for Bamendankwe and Akum due to their proximity. A FGD was held for each of the other locations, making a total of five FGDs for this study. This was necessary to discuss and further understand the common problems with biogas technology and the contribution of biogas adoption to household poverty reduction. Observation guides were used to understand how biogas energy is used in households. The daily biogas consumption in households was reported in litres (by the respondents) and the corresponding volume in cubic metres was calculated. Field research was undertaken by a gender-sensitive team of six experienced experts. The impact assessment was captured mainly through a 'before' and 'after' comparison of variables of interest in the questionnaire (Crawford et al. 2008; Khandler et al. 2010; Balgah et al. 2012).

Table 4.1. Variables and sampling units

Quantitative	Qualitative	Sampling unit (Community)	Number of respondents
Fuelwood consumption (kg)	Social relationship at household	Akum	4
Cost of fuelwood (FCFA)	Health of household members	Awing	6
Household income (FCFA)	Level of satisfaction with biogas technology use	Bamendankwe	9
Age of household head (years)	Level of satisfaction with biogas technology management	Kedjom Ketinguh	4
Gender of household head (Number)	Food consumption times	Santa Mbei	6
Household size (Number)	Problems with biogas technology	Santa Njong	9
Number of dairy cattle heads (Number)		Vekovi	7
Size of biogas plant (m^3)			
Biogas consumption (m^3/day)			
Total			**45**

4.3.3. Sampling techniques

The research made use of purposive, stratified and random sampling techniques. This study purposely targeted biogas users who benefited from the biogas projects. The first level of stratification allowed for the identification of beneficiary communities (sampling units) to be included in the survey. This method led to the identification of all 45 biogas plants in the study area, being part of the 1000 biogas plants that were expected to be constructed by the HPI project in Cameroon. This was the second level of stratification. The third level was gender-based, including male and female beneficiaries. In each gender stratum, sampling units were then randomly drawn. This led to the identification of 45 respondents (27 males and 18 females) who were retained for this study, as shown in Table 4.1. The number of females was lower since fewer women originally benefitted from the project. In addition, the higher number of males resulted from the fact that most households in the study areas were headed by males.

This study was limited to a small number of small-scale biogas plants, which represent a very small share of the energy supply in Cameroon. Notwithstanding, these biogas plants were useful to justify how energy deficiency persists in households despite the available potential.

4.3.4. Data analysis

This study applied the sustainable livelihoods framework (SLF) to demonstrate how increased access to energy from small-scale biogas technology can impact the livelihoods of beneficiaries. The livelihoods framework is used to unravel the complexity of people's livelihoods, especially the livelihoods of poor people, whether they be rural or urban (Soas 2019). It seeks to understand the various aspects of a person's livelihood; the strategies and objectives pursued, and associated opportunities and constraints. Quantitative data were recorded in the SPSS (Statistical Package for the Social Sciences) software version 20.0 and the descriptive data analysis was performed for the means and standard deviations. Based on the livelihood portfolio (that is, human, physical, financial and social assets) of the SLF (Scoones 1998; DFID 1999), the livelihood situation of targeted households pre and post-HPI project was compared to identify any significant differences. Qualitative data were used to triangulate and interpret the results. Apart from assessing the livelihood situation of the households due to the use of biogas energy, the environmental benefits were assessed to reveal the global warming potential (GWP) or decarbonization potential of adopting biogas technology. The estimation of the GHG emissions from the combustion of biogas in $kgCO_2e$ was done using equation 4.1. In the calculations, the energy (calorific) value of biogas was considered to be approximately 20 MJm^{-3} (Kizilaslan & Kizilaslan 2007). The GHG emission factors of biogas were $54600mgCO_2MJ^{-1}$; $5mgCH_4MJ^{-1}$, and $0.1mgNO_2MJ^{-1}$ (Mengistu et al. 2016). All the households burnt the biogas produced in biogas stoves and used it for cooking.

$$E = \sum_{i=1}^{n} (C_i\ x\ EF_{CO_2}\ x\ GWP_{CO_2} + C_i\ x\ EF_{CH_4}\ x\ GWP_{CO_2} + C_i\ x\ EF_{N_2O}\ x\ GWP_{N_2O}) = \sum_{i=1}^{n} (C_i\ x\ (EF_{CO_2} + 25\ x\ EF_{CH_4} + 298\ x\ EF_{N_2O}) \qquad (4.1)$$

where, E = GHG emissions in kg from the combustion of biogas; n = total number of sample households; C_i = amount of biogas consumed by the sample households; C_i = amount of biogas consumed by a sample household 'i'; EF_{CO_2} = CO_2 emission factors for biogas; EF_{CH_4} = CH_4 emission factor for biogas; EF_{N_2O} = N_2O emission factor for biogas; GWP = global warming potential for the GHG indicated. Equation 4.2 was used to estimate the annual GHG emissions that can be reduced due to the use of biogas plants in the rural households (Mengistu et al. 2016).

$$E_{CO_2e} = YC \times P_{CH_4} \times GWP_{CH_4} \times R \quad (4.2)$$

Where E_{CO_2e} = average annual GHG emission of methane from the biogas plants in $kgCO_2e$; YC = annual average biogas generation from the biogas plants in kg, given that the average daily biogas production is $5.6m^3$ and $1m^3$ of biogas = 0.7 kg; P_{CH_4} = volume fraction of the methane in biogas which was 56%; GWP_{CH_4} = GWP of methane in CO_2e, which is 25; R = average fugitive emissions of methane which is about 10%.

4.4. Results and discussions

4.4.1. Socio-economic description of the sample population

Male beneficiaries of the HPI biogas project constituted 60% of the final sample, while 40% were females. This largely reflects the situation in Cameroon, where patriarchal systems exist and male dominance in terms of access to resources is common (Balgah 2016). It can be seen in Figure 4.1 that less than 14% of the household heads completed secondary school and above. In terms of their highest level of instruction, the majority had completed primary school (over 46%, less than the national average of about 72%). The other 40% did not complete primary school. This suggests that households are generally poor in human capital. The results resonate with previous knowledge that the poor in developing countries, at least from an educational perspective (human capital) perspective, are found mainly in rural areas (Kolawole et al. 2017; UNEP 2017). In 2015, the youth literacy rate for Cameroon was 83.8 % (Knoema 2020). Our results showed 40% of beneficiaries are probably illiterate since they did not complete primary school, suggesting that the project fulfilled its aim in reaching out to the poorest in the target communities.

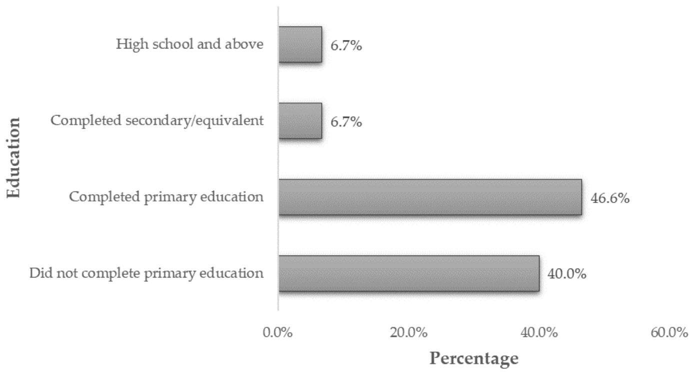


Figure 4.1. Level of education of biogas users

The average household size was 8 persons. The age of the respondents and household size influenced the amount of labour and revenue available for the successful construction of biogas plants. The ages of the household heads (respondents) ranged from 26 years to 71 years. The average age of the respondents was about 50 years. Table 4.2 is a summary of the results.

Table 4.2. Average respondents' age and household size

Variable	Min.	Max.	Mean	Std. dev.
Age of respondent (years)	26	71	48.90	10.93
Household size (number)	2	15	7.54	2.34

4.4.2. Impact of biogas technology on livelihoods

In this section, the impacts of the biogas project are presented and discussed based on the SLF livelihood asset portfolio.

Human capital

The impacts of the intervention on human capital were captured by comparing the variables before and after the intervention as shown in Table 4.3.

Table 4.3. Impact of access to biogas technology on human capital

Variable	**Period**	**Min.**	**Max.**	**Mean**	**Std. dev.**	**p-value**
Daily food consumption	Before biogas energy access	2	3	2.72	0.45	0.09
	After biogas energy access	2	4	3.00	0.63	
Weekly meat/fish consumption	Before biogas energy access	1	8	3.06	2.18	0.06
	After biogas energy access	1	8	4.06	2.20	

On average, the daily number of times meals that were consumed is approximately 3. There was no difference after adopting biogas technology. Notwithstanding, protein-rich food (meat and or fish) was consumed three times (p = 0.06) per week as opposed to two times before the adoption of biogas technology. Both male and female beneficiaries of households had a similar situation. The results are significant at the 10% level, which is noticeable since the sample is rather small. They can be interpreted so that beneficiary households enjoy increased consumption, presumably as a result of the decrease in fuelwood expenditures after the adoption of biogas technology. This is not different from the results obtained by Balgah et al. (2018). Although the level of significance seems weak, the difference can be very important from an economic perspective (Rommel & Weltin 2017). The analysis of qualitative data shows that households consume a variety of foods due to increased crop diversification. The diversification resulted from the use of bio-slurry (fertilizer) to grow more crops than was the case before the technology intervention. In fact, 89% of beneficiaries attested to have witnessed an increase in food types consumed since the inception of the technology. They attested to the fact that more food varieties have also increased food sales (especially of vegetables). The increased household income is used to purchase protein-rich food, especially additional fish and/or meat. Consumption of more nutritious food varieties coupled with a reduced cooking workload created more rest and leisure time for beneficiaries, especially women who are often in charge of domestic work in developing countries (Balgah 2016). The reduction of toxic gases, such as smoke from biogas stoves, was found to reduce ocular problems and few respiratory diseases were observed for beneficiaries. This was confirmed during the focus group discussions. One of the beneficiaries clearly said the following:

> *'Since we were introduced to this biogas technology, we are feeling better healthwise. The smoke and wood ash that used to enter our eyes when we were struggling with fuelwood is no more. Two group members who always had coughs told me last week that this greatly subsided without any medication. I am very sure the cough was coming from the smoke in the fuelwood kitchen. We are grateful to HPI for this wonderful gift (the biogas system)'* [Female beneficiary from Vekovi, Cameroon].

This information points to the conclusion that biogas technology positively impacted the health of members of households that adopted biogas technology. This was acknowledged by 73.3% of all interviewed beneficiaries. The results are similar for both the female and male-headed beneficiary households (74.1% for females and 72.2% for males). Our results mirror those from previous research (Abadi et al. 2017; Pizarro-Loaiza et al. 2021). Other similarities to our case study reported by the authors include a reduction in workload, especially with the purchase of fuelwood by women and time savings in cooking due to the ease of cooking with a biogas stove (as reflected in Roubík & Mazancová 2019).

Physical capital

Physical capital was evaluated on the basis of the number of cattle and farm size on which fertiliser from biogas was used to produce crops and improve pasture. The average number of dairy cattle significantly increased after the adoption of biogas technology by households (from 1 to 3.14±4.74, $p = 0.003$). The benefits of utilising biogas seem to have motivated farmers to boost their stock of dairy animals, as this ensures a regular and stable supply of manure to feed into the bio-digester. However, information from focus group discussions showed that some farmers obtained new stock to replace the former ones. In such situations, the biogas project only provided an additional benefit. The results of Table 4.4 show that the average area of agricultural land cultivated by the households was proportionately reduced to the adoption and use of the biogas digester (1.59±1.55 before and 1.22±1.04 with biogas, respectively, $p = 0.05$). This relates to studies conducted by Shallo et al. (2020) and Lwiza et al. (2017). On the other hand, the area on which pasture for the dairy is now developed has increased (0.65±0.48 before and 0.71±0.57 after, respectively), even if the increase was not statistically significant. This is expected, as more land was needed for feeding cattle than for agricultural production. With land as a limited resource, it was only logical that agricultural land is transformed into pasture lands.

Information from FGDs and KII suggests that many farm households no longer cultivate on distant farms because productivity increased significantly on home gardens and other plots closer to the house since they started applying slurry left obtained as a by-product of the biogas production process. They no longer saw the need to continue travelling long distances for cropping because the yield from the nearby farm plots on which slurry is used became very high. As reported by a beneficiary:

Table 4.4. Impact of biogas technology adoption on the physical capital of beneficiaries

Variable	Period	Min	Max	Mean	Std. Dev.	p-value
Number of cattle owned by household	Before biogas energy access	2	2	2	0.0	0.00
	After biogas energy access	1	5	3.1	4.7	
Land for agricultural production	Before biogas energy access	0.5	6.0	1.6	1.6	0.05
	After biogas energy access	0.5	4.0	1.2	1.0	
Land for pasture development	Before biogas energy access	0.3	1.5	0.7	0.5	0.52
	After biogas energy access	0.4	2.5	0.7	0.6	

> *'Since we joined this program, we have been generating more manure by ourselves. We then use it to fertilise our farms around the compound. We are also growing new garden crops like huckleberry and tomatoes, which we were buying from the market. Last year, I harvested 2 bags [equivalent to 100 kg] of huckleberry and 6 baskets of tomatoes [approximately 150 kg]. We ate half of our harvest and sold the rest. The additional money was used to buy books and pay school fees for our children who attended school regularly last year. Besides, we no longer need to beg and cultivate farms far off from the village'.* [Male beneficiary in Bamendankwe, Cameroon].

Furthermore, the fact that slurry was available for fertilisation of pasture, motivated them to increase their pasture lands. However, a limitation to this is the number of cattle owned, as women, in particular, cannot sustain a large number due to limited access to or control of the land from which pasture is developed (Balgah 2016). According to Fon (2011), about 75.7% of women in Cameroon do not have control over arable land. These women persistently have less access to productive resources than men (Njikam et al. 2021). This probably explains why the land under cultivation with bio-fertiliser is significantly lower for women than men (0.5ha and 0.9ha, respectively, p = 0.00). However, a female beneficiary in Njong reported that: '*It is possible for other women and me today to acquire land for biodigester construction through purchase and family*'. Fon (2011) further emphasizes that rural women in Cameroon can access arable land through other sources, in order of importance, family, soliciting, gift, renting and communal.

Financial capital

Reasonably, the dominant impact of adopting the biogas technology can be seen in the increase in household income and expenditure, as shown in Table 4.5. Quantitative and qualitative data reveal that farmers who adopted biogas plants witnessed a tremendous upsurge in their financial assets in terms of the reduction in the expenditures on other energy sources like fuelwood and charcoal as well as on chemical fertilizers.

During a year, farmers now spend FCFA 71,120 (≈US$ 118) lower on fuelwood and FCFA 20,610 (≈US$ 34) less on inorganic fertilizers. This showed that biogas technology can replace fuelwood used for cooking. This is also evident that bio-fertilizer can replace inorganic fertilizers in crop fields. This is best understood within the backdrop of the increased number of livestock stimulated by technology adoption.

Table 4.5. Financial impacts of adopting biogas technology

Variable	Period	Min	Max	Mean	Std. Dev.	P-value
Quantity of fuelwood used yearly (in trucks)	Before energy access	30.4	152.1	65.5	26.9	0.005
	After energy access	6.1	91.3	29.7	18.3	
Annual expenditures on fuelwood/FCFA	Before energy access	0.0	307,000	143,040	115,550	0.004
	After energy access	0.0	307,000	71,120	73,770	
Annual expenditures on inorganic fertilisers/FCFA	Before energy access	0.0	181,000	50,550	32,390	0.001
	After energy access	0.0	162,100	29,990	30,110	
Revenue from sales/FCFA	Before energy access	0.0	203, 010	32,522	50,601	0.035
	After energy access	0.0	661,000	87,300	135,150	

Note: 1 US $ = FCFA 600 (adjusted to the nearest FCFA)

The increased crop production and productivity due to bio-slurry application on farms provided households with excess food for the market, within the subsistence-based agricultural systems dominant in rural areas of Cameroon. This resulted in an average annual increase of FCFA 54,680 (≈US$ 91) from sales of food crops per household and year. The estimation of the income from the sale of crops has been done only for the two main crops (beans and maize) most cultivated in the region. A calculation of the net reduction on fuelwood and chemical fertilizer for one year and the net income earned from increased crop sales gives a total of FCFA 146,310 (≈US$ 244) per given household per annum. This justifies a significant increase in household income of 73% concerning previous annual household incomes before the technology adoption. This increase in financial capital also led to an estimated increase in annual savings of FCFA 75, 600 (≈US$ 126). Adopting biogas has vested significant economic benefits for adopters. Therefore, biogas technology adoption can be considered an important means of boosting the incomes of farmers in developing countries, particularly in rural areas. This can also help in lifting them out of poverty. Similar findings have been reported by Mukumba et al. (2016) in South Africa; and Of et al. (2019) in Rwanda. These results and previous findings, therefore, lead us to conclude that adopting small-scale biogas technology can bring economic benefits to beneficiaries.

Social capital

The results of the FGD revealed that, on average, almost 90% of all beneficiaries in each community were members of a social group from which information and experience are shared. In addition, they benefited through the sharing of skills and knowledge by members who were more familiar with biogas technology. Consequently, they got consultation and expert services from fellow members in the management of their biogas plants for free or at prices lower than prevailing market rates.

Another interesting feedback from focus group discussions was the participation of male children in cooking in the studied households as they enjoyed doing so with biogas than previously was the case with fuelwood. This ensures the sharing of the cooking burden with male members of the family as well as a shift in family time use. The workload associated with cooking was highly reduced for the women and girls in these households, who spent more time studying. Over 50% of all households reported improved performance of children (especially the girls) in school examinations than before the technology. Households socialized more after the intervention. This is evident in that all members of the households declared that they spent more time together. Due to the adoption of biogas technology, families spend more time together in the evening around the biogas stove, even during electricity failures that are very common in the studied communities. These additional benefits identified in this study add to the other benefits identified of biogas technology to rural communities (Ferroukhi et al. 2016) in improving the livelihoods of households and reducing rural household energy deficiency. As a beneficiary explains:

> *'When HPI first arrived in our community, we did not have this type of group that could allow us to learn things that could help us improve our lives. Today, we can understand how to make and use biogas. More*

organisations are now working with our [new] groups, giving us financial support for our other activities (such as farming). This additional support is helping us to send our children to school. We are attracting more respect from other community members now. We owe all of this to HPI, who encouraged us to join groups during the introductory phase of the biogas project' [Male beneficiary from Santa, Cameroon].

The HPI intervention on biogas technology in this study demonstrates that energy supply in rural Africa is possible if the physical, human, social and financial capitals are applied to mobilize the available energy potential. The dynamics of these capitals is still unclear to many decision-makers in the Cameroon as it varies from one geographical location to the other. Therefore, there is need to understand these specific dynamics in order to improve the sustainability of such interventions. In addition, systems studies focused mainly on the resource potential/mobilisation and governance are needed inform decisions and actions required to improve these interventions.

Natural capital

Biogas technology provides several environmental benefits including reduction of deforestation due to household fuelwood demand (Subedi et al. 2014), improvement of household sanitation (Brown 2006), reduction of indoor pollution (Rees et al. 2019) and of GHG emissions (Tagne et al. 2021). Out of the 45 biogas plants, 35 (87.5%) were fed with cow dung, while 10 (13.5%) were fed with pig waste. This contributed to improving the sanitation in the animal barns. The biogas plants varied in size from 6 - 10m^3, with an estimated average size of 8m^3. The average daily biogas production per 8m^3 biogas plant was 5.6 m^3/day. The average methane content of biogas was 56% of the biogas produced. On average, fugitive emissions comprised 10% of the biogas produced. From equation 4.2, the annual GHG reduction from the use of the 8m^3 biogas was estimated to be 2866 tCO_2e per biogas plant (per household). This implies that biogas is a better alternative to fuelwood used in households of non-biogas users. From this, the use of biogas in a household could lead to the reduction of 2866 tons of fuelwood in each household in a year. Mobilising the biogas potential in Africa would lead to significant decarbonisation of energy supply.

4.5. Conclusion and policy recommendations

4.5.1. Conclusion

This study has demonstrated that the energy deficiency amid huge renewable energy potential is detrimental to the sustainable development of Cameroon. Based on the analysis of the asset portfolio of the Sustainable Livelihood Framework and zooming into the role of small-scale biogas technology, we observed that adopting biogas technology created significant impacts on the different forms of livelihood capital assets. The strongest impacts were observed on the financial capital front. Considering biogas as an environmentally friendly energy source, an 8m^3 sized biogas plant could contribute to the mitigation of up to 2866 tCO_2e per year.

With the available unexploited energy potential and a generally supportive energy policy and institutional frameworks, we contend that a Cameroonian energy revolution is possible. This, however, demands the engagement of the international community and all local stakeholders to commit towards enhancing a just and sustainable clean energy transition according to the Agenda 2030. This is visible in this Cameroon study, where the energy initiative of an international non-governmental organization (Heifer Project International), was able to improve the livelihoods of rural beneficiaries as a steppingstone to sustainable energy supply and development.

4.5.2. Policy recommendations

Future policies to revolutionize energy access in Cameroon should be largely contingent on renewable energy to contribute to long-term development in Cameroon. Renewable energy sources (including biogas) should be made available, affordable and reliable for all, as clearly spelt out in sustainable development goal 7 of Agenda 2030. While the challenge would be to mobilize the available potential, designing supply projects to create an immediate positive impact on the livelihood of all persons, especially those in rural areas, is even more necessary. We contend that this can contribute to reducing poverty on the continent, partly and directly through reduced energy costs at the household level and indirectly by attracting foreign direct investments. Until this happens, energy deficiency amid abundance will continue to play a major role in hindering sustainable development in Cameroon.

References

Abadi N, Gebrehiwot K, Techane A, Nerea H. 2017. Links between biogas technology adoption and health status of households in rural Tigray, Northern Ethiopia. Energy Policy. doi: 10.1016/j.enpol.2016.11.015

Abdelrazik MK, Abdelaziz SE, Hassan MF, Hatem TM. 2022. Climate action: Prospects of solar energy in Africa. Energy reports. Volume 8, 11363-11377. doi: 10.1016/j.egyr.2022.08.252

Africa Progress Panel. 2015. Africa Progress Report 2015 - Power, People, Planet: Seizing Africa's energy and climate opportunities. ISBN 978-2-9700821-6-3.

African Union. 2015. Agenda 2063: The Africa we want - Background Note. 1–20. Available from https://au.int/sites/default/files/documents/33126-doc-01_background_note.pdf (accessed 12 April 2021).

Balgah RA. 2016. Using Access and Control Profiling to Unlock Gender Group Differences in Some Communities in Rural Cameroon. *Asian Journal of Agricultural Extension, Economics and Sociology*, 12 (3), pp. 1-11.

Balgah RA, Buchenrieder G, Mbue I. 2012. When Nature Frowns: A comprehensive impact Assessment of the 2012 Babessi floods on people's livelihoods in rural Cameroon. *Journal of Disaster Risk Studies* 7, (1), Art. #197, 8 pages. doi: 10.4102/jamba.v7i1.197.

Balgah RA, Mbue IM, Ngwa KA. (2018). The impacts of renewable energy on livelihoods. A case study of biogas adoption in Cameroon, *International Journal of Development and Sustainability* 7(1), pp. 220-239.

Bonan J, Pareglio S, Tavoni M. 2017. Access to modern energy: A review of barriers, drivers and impacts. Environment and

Development Economics, 22(5), 491–516. doi: 10.1017/S1355770X17000201.

Brown VJ. 2006. Biogas, a bright idea for Africa. Environmental Health Perspectives, 111(7), 883. Available from https://ehp.niehs.nih.gov/doi/epdf/10.1289/ehp.114-a300 (accessed on 20 August 2021).

Crawford B, Herrera M, Almanza M, Balladares E. (2008). *Impact Assessment of the SUCCESS Program Livelihood Activities in the Padre Ramos Estuary Nature Reserve of Nicaragua.* Coastal Resources Center, University of Rhode Island and Centro de Investigación de Ecosistemas Acuaticos, Universidad Centroamericana.

DFID. 1999. Sustainable Livelihoods Guidance sheets, http:www.nssd.net/pdf/sectiono.pdf (Accessed on 20 November 2015).

Eba'a Atyi R, Ngouhouo P, Mvondo A, Ngoungoure M, Sufo K. 2016. Economic and Social Importance of Fuelwood in Cameroon. *International Forestry Review,* 18 (2), pp.1-14.

Ferroukhi R, Lopez-Peña A, Kieffer G, Nagpal D, Hawila D, Khalid A, El-Katiri L, Vinci S, Fernandez A. 2016. Renewable Energy Benefits: Measuring the Economics. IRENA International Renewable Energy Agency.

Fon D. 2011. Access to Arable Land by Rural Women in Cameroon. Tropicultura, 29(2), 65–69.

Hafner M, Tagliapietra S, de Strasser L. 2018. Prospects for Renewable Energy in Africa. In: Energy in Africa. SpringerBriefs in Energy. Springer, Cham. doi: 10.1007/978-3-319-92219-5_3

HPI (Heifer Project International Cameroon). 2015. Evaluation Report on the Pilot Project on Domestic Biogas in the Western Highlands of Cameroon, HPI, Cameroon.

Human JM. 2021. African countries continue to have the highest poverty rates in the world. Available from https://www.developmentaid.org/#!/news-stream/post/84943/highest-poverty-rates-in-africa (accessed on 24 May 2021).

IEA. 2022. Africa Energy Outlook 2022. International Energy Agency. Available from https://iea.blob.core.windows.net/assets/220b2862-33a6-47bd-81e9-00e586f4d384/AfricaEnergyOutlook2022.pdf (Accessed on 9 August 2023).

IEA, IRENA, UNSD, World Bank, WHO. 2020. Tracking SDG 7: The Energy Progress Report.World Bank, Washington DC. © World Bank. License: Creative Commons Attribution – Non-Commercial 3.0 IGO (CC BY-NC 3.0 IGO).

IHA (International Hydropower Association Limited). 2020. 2020 Hydropower status report.

Innocent NM, Bitondo D, Balgah RA. 2016. Climate Variability and Change in the Bamenda Highlands of North Western Cameroon: Perceptions, Impacts and Coping Mechanisms. *British Journal of Applied Science and Technology*, 12 (5), pp.1-18.

Khandler RS, Koolwal GB, Samad HA. 2010. Handbook on impact evaluation: Quantitative methods and practices. Washington, DC: The World Bank.

Kimengsi JN, Mukong AK, Balgah RA. 2020. Livelihood diversification and household well-being: insights and policy implications for forest-based communities in Cameroon. Society and Natural Resources 33(7), pp. 876-895.

Kidmo DK, Deli K, Bogno B. 2021. Status of renewable energy in Cameroon.

Kizilaslan N, Kizilaslan H. 2007. Turkey's biogas energy potential. Energy Sources, Part B: Economics, Planning and Policy, 2(3), 277–286. doi: 10.1080/15567240600629377.

Kolawole A, Adesola S, De Vita G. 2017. A Disaggregated Analysis of Energy Demand in Sub-Saharan Africa. International Journal of Energy Economics and Policy, 2017(2), pp. 224-235.

Lwiza F, Mugisha J, Walekhwa PN, Smith J, Balana B. 2017. Dis-adoption of Household Biogas technologies in Central Uganda. Energy for Sustainable Development, 37, 124–132. doi: 10.1016/j.esd.2017.01.006

Mboumboue E, Njomo D. 2018. Biomass resources assessment and bioenergy generation for a clean and sustainable development in Cameroon. Biomass and Bioenergy, 118, 16–23. doi: 10.1016/j.biombioe.2018.08.002

Melber H. 2017. Development Studies and the SDGs – Mapping an Agenda, Lecture at CERES Summer School 2017 on: Engaging with the Sustainable Development Goals (SDG): Gaps, Opportunities and Challenges, CERES School of International Development Utrecht, 22 June 2017, and published in the EADI Policy Paper Series, August 2017.

Mengistu MG, Simane B, Eshete G, Workneh TS. 2016. The environmental benefits of domestic biogas technology in rural Ethiopia. Biomass and Bioenergy, 90, 131–138. doi: 10.1016/j.biombioe.2016.04.002.

Morrow K. 2018. Energy and the Sustainable Development Goals. Sustainable Development Goals: Law, Theory and

Implementation, 1, 149–172. doi: 10.4337/9781786438768.00014

Mukoro V, Sharmina M, Gallego-Schmid A. 2022. A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value?. Energy Research and Social Science 88, 102530. doi: 10.1016/j.erss.2022.102530.

Mukumba P, Makaka G, Mamphweli S. 2016. Biogas Technology in South Africa, Problems, Challenges and Solutions. International Journal of Sustainable Energy and Environmental Research, 5(4), 58–69. doi: 10.18488/journal.13/2016.5.4/13.4.58.69

Njikam O, Elomo TZ, Mbengono CP, Abossolo IPD. 2021. Target women farmers' structural disadvantages to improve rural productivity and food security in Cameroon. Policy brief. Pancanaka, 1(03), 14. Available from https://kebijakankesehatanindonesia.net/images/2019/policy_brief_penetapan_kelas_standar_pelayanan_jkn_sebagai_amanah_uu_sjsn.pdf

Of M. 2019. Department Of Mechanical And Energy Engineering Master's Thesis: Opportunities of small scale biogas plants to overcome lack of cooking energy.

Oginni, O. S., Omojowo, A. D. (2016). Sustainable development and corporate social responsibility in Sub-Saharan Africa: Evidence from industries in Cameroon. Economies, 4(2). doi: 10.3390/economies4020010

Ogunniyi E. 2019. Paradox of Africa's renewable energy potentials and quest towards powering Africa. IEEE PES/IAS PowerAfrica. doi: 10.1109/PowerAfrica.2019.8928927.

Ouedraogo NS. 2019. Opportunities, Barriers and Issues with Renewable Energy Development in Africa: a Comprehensible Review. Curr Sustainable Renewable Energy Rep 6, 52–60. Doi: 10.1007/s40518-019-00130-7.

Ouedraogo NS. 2017. Africa energy future: Alternative scenarios and their implications for sustainable development strategies. Energy Policy, 106(March), 457–471. doi: 10.1016/j.enpol.2017.03.021.

Oyinola MA, Adededji AA, Olabisi N. 2020. Technology, energy use and agricultural value addition nexus: an exploratory analysis from SSA Countries. *Economic Change and Restructuring* 2020, 1-34. doi: 10.1007/s10644-020-09286-5.

Pizarro-Loaiza CA, Antón A, Torrellas M, Torres-Lozada P, Palatsi J, Bonmatí A. 2021. Environmental, social and health benefits of alternative renewable energy sources. Case study for household biogas digesters in rural areas. Journal of Cleaner Production, 297. doi: 10.1016/j.jclepro.2021.126722

Quitzow R, Roehrkasten S, Jacobs D, Bayer B, El Mostafa J, Waweru Y, Matschoss P. 2016. The Future of Africa's Energy Supply. Potentials and Development Options for Renewable Energy.

Rees N, Wickham A, Choi Y. 2019. Silent Suffocation in Africa Air Pollution is a growing menace, affecting the poorest children the most. World Health Organization, 1–14. Available from https://www.unicef.org/media/55081/file/Silent suffocationinafricaairpollution2019.pdf.

Rommel J, Weltin M. 2017. Is there a Cult of Statistical Significance in Agricultural Economics?

www.ageconsearch.umn.edu/record/261998/files/Rommel _150pdf (accessed on 22 September 2017).

Roubík H, Mazancová J. 2019. Small-scale biogas plants in central Vietnam and biogas appliances with a focus on a flue gas analysis of biogas cook stoves. Renewable Energy, 131, 1138–1145. doi: 10.1016/j.renene.2018.08.054.

Sanoh A, Kocaman AS, Kocal S, Sherpa S. 2014. The economics of clean energy resource development and grid interconnection in Africa. Renewable Energy 62, 598-609. doi: 10.1016/j.renene.2013.08.017

Scoones I. 1999. Sustainable rural livelihoods: a framework for analysis. IDS Working Paper No. 72.

Shallo L, Ayele M, Sime G. 2020. Determinants of biogas technology adoption in southern Ethiopia. Energy, Sustainability and Society, 10(1), 1–13. doi: 10.1186/s13705-019-0236-x.

Soas. 2019. The livelihood framework. Available from https://www.soas.ac.uk/cedep-demos/000_P516_EID_K3736-Demo/unit1/page_15.htm (accessed on 12 May 2019).

Subedi M, Matthews RB, Pogson M, Abegaz A, Balana BB, Oyesiku-Blakemore J, Smith J. 2014. Can biogas digesters help to reduce deforestation in Africa? Biomass and Bioenergy, 70, 87–98. doi: 10.1016/j.biombioe.2014.02.029.

Tagne RFT, Dong X, Anagho SG, Kaiser S, Ulgiati S. 2021. Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa. Environment, Development and Sustainability, 23(10), 14799–14826. doi: 10.1007/s10668-021-01272-9.

Toh FA, Angwafo, TE, Ndam LM, Antoine, MZ. 2018. The Socio-Economic Impact of Land Use and Land Cover Change on the Inhabitants of Mount Bamboutos Caldera of the Western Highlands of Cameroon. Advances in Remote Sensing, 07(01), 25–45. doi: 10.4236/ars.2018.71003.

UNEP. 2017. Atlas of Africa Energy Resources. Nairobi, Kenya: United Nations Environment Programme (UNDP).

World Bank. 2021. Cameroon Electricity Access 1991-2021. Available from https://www.macrotrends.net/countries/CMR/cameroon/electricity-access-statistics (accessed on May 2020).

5. Understanding factors influencing household's choice of small-scale biogas plant size in Cameroon using the multivariate probit model.

Status: Paper submitted for publication

Contributions:

Hynek Roubík and Chama Theodore Ketuama conceived the idea for the paper. Chama Theodore Ketuama collected, analysed the data and wrote the original manuscript. Revisions were done by Chama Theodore Ketuama and Hynek Roubík. Supervision was done by Hynek Roubík.

Abstract

Rural households in Cameroon continue to rely heavily on fuelwood and charcoal for their energy needs, particularly for cooking. This practice is unsustainable, necessitating the adoption of modern, clean energy alternatives. Biogas, a promising renewable energy source, has been introduced to rural areas in Cameroon. However, its diffusion remains slow. Rural households are exhibiting varied adoption behaviours, which manifests in the selection of different biogas plant sizes. To understand this adoption behaviour, the multivariate probit regression analysis was used to assess the factors influencing rural households' choice of small-scale biogas plant sizes and emerging adoption pathways towards sustaining rural biogas production and use. The findings show that factors such as household income and available opportunities (availability of feedstock, sufficient water and subsidy) are the main factors influencing the choice of biogas plant size in rural areas of Cameroon. In addition, the level of capabilities gained through

awareness campaigns, access to training and masons influenced the size of the biogas plant that was selected. Finally, the choice of a biogas plant size was motivated by the perceived benefits from it. The identified pathways to sustain biogas technology would be anchored on three options: the productive-consumptive use of biogas, cost-sharing to reduce the financial burden, and the pathway that empowers the vulnerable rural population to adopt and sustain their biogas plants.

Keywords: Biogas, clean cooking, behaviour change, energy access, energy transition, sustainability, Cameroon.

5.1. Introduction

The current global energy transition is fundamentally shifting away from fossil fuels (e.g. coal, crude oil, and natural gas) towards cleaner, renewable energy sources (e.g. solar, wind power, solar power, bioenergy and hydroelectricity, including tidal energy). Despite investments in renewable energy, many people, especially in low-income countries, still lack access to clean energy. Research has identified several causes of low access, including high cost of investment, limitations in infrastructure, poor access to technology, policy and regulatory barriers, continuing dependence on fossil fuels and prioritization of other alternatives with immediate economic growth rather than long-term goals (Trotsenburg 2023; Qadir et al. 2021; Ketuama et al. 2022). According to 2022 data, approximately 685 million people worldwide still lack access to electricity, while 2.1 million still depend on polluting energy sources for cooking (IEA et al. 2024). Most of this population is residing in sub-Saharan Africa (SSA). In Cameroon, a sub-Saharan country, only 65.4% of the population has access to electricity in 2022 (IEA et al. 2024). Access to electricity is higher in urban areas, reaching up to 94.7%. In rural areas, only 24.8% of the population has access to electricity, and only 26% has access to clean energy. In Cameroon, like other developing countries, the lower access to clean energy in rural areas is partly caused by the difficulty of extending expensive infrastructure to some geographically isolated areas. Other factors, such as low population density, limited economic activities, and insufficient government funding, have contributed to low access to energy (World Bank 2018). To improve energy access in rural areas, often cost-effective, sustainable off-grid technologies such as biogas, solar photovoltaic, wind energy, etc, can be very useful.

Rural areas play a significant role in safeguarding bioenergy transition, contributing substantially to its sustainability and resilience. Rural households, for example, make decisions to adopt biogas technology, identify and mobilise resources or opportunities, and implement activities related to biogas production and use. Understanding the household choice of biogas plant on one hand and the behaviour towards biogas technology on the other hand, becomes indispensable for a specific context. Leveraging contextual capabilities, opportunities and motivation (COM) to biogas technology is essential in achieving the triple bottom line (TBL) of sustainability. The successful transition to small-scale biogas energy in rural areas necessitates its economic, environmental, social, and to some extent, spiritual sustainability (Fulford 2015).

Behaviour change is a critical factor in achieving sustainable and equitable energy access (Mundaca et al. 2022). While technological advancements and infrastructure development are essential, the adoption and efficient use of energy technologies often depend on individual and community behaviours. One of the behavioural change models applicable to rural household biogas technology is the COM-B model. The COM-B model is a valuable asset for policymakers and researchers that provides a robust framework for understanding and predicting rural household biogas adoption, paving the way for effective interventions to promote sustainable energy solutions (Michie et al. 2011).

5.2. Theoretical framework

The theoretical framework used in this study is based on the COM-B (behavioural) change model developed by Michie et al. (2011) as part of the Behaviour Change Wheel (BCW). It is widely used in health promotion, public health interventions, and other fields, such as energy access, to understand and influence behaviour. The model identifies three key components that are necessary for any behaviour to occur: Capability, Opportunity, and Motivation. The COM-B model asserts that an individual's capabilities (psychological and physical), opportunities (social and physical), and motivations (automatic and reflective) interact with each other to influence Behaviour. Capability or agency refers to the individual's ability to perform a behaviour. This includes physical and psychological capability. Physical capability includes the physical skills or abilities to perform a behaviour. Psychological capability includes the mental or cognitive skills needed to perform the behaviour, including knowledge, decision-making skills, and attention. Opportunity refers to the social environment of cultures and norms or the physical environment of objects and events with which people interact. This comprises the external factors that make the behaviour possible or easier. Opportunity can be divided into physical and social. Physical opportunity comprises environmental factors such as time, resources, or access to facilities. Social opportunity includes the influence of social norms, culture, and interpersonal support. Motivation refers to the internal processes that energize and direct behaviour. Motivation is comprised of reflective intentions, evaluations and values, and/or automatic habits, emotions and instincts that direct human behaviour. Motivation can be reflective or automatic. Reflective motivation involves conscious thought processes, such as beliefs, intentions, and plans. Automatic motivation refers to unconscious influences, such as emotional responses, habits, or impulses.

5.3. Current energy context and biogas technology in rural areas of Cameroon

Due to a lack of clean energy sources, rural households in Cameroon are still heavily dependent on fuelwood and charcoal to meet their household energy needs. This demand is satisfied at the expense of land degradation and deforestation resulting in long-term environmental changes. Conversely, biogas technology offers several benefits, combining energy production, waste management, fertilizer production, and a healthier indoor environment at the household level, as well as reducing greenhouse gas (GHG) emissions at the global level. Biogas systems contribute to achieving the goals of the 2030 Agenda, directly sustainable development goal (SDG) 7 and indirectly 11 others (Obaideen et al. 2022; Mukisa et al. 2022). Rural areas in Cameroon are characterised especially by high levels of poverty and poor living conditions. These areas lack economic, social and physical infrastructure opportunities, which renders them unsustainable and leads to poor quality of life for the residents (Mbah & Franz 2021). Due to the economic (financial), technical and social challenges of adopting biogas technology, the transition to small-scale biogas energy has been very slow in rural areas of Cameroon despite the many biogas initiatives implemented by the government and its partners. Past biogas initiatives in Cameroon and other developing countries have focused on developing the national biogas socio-technical system to sustain the biogas sector (Ghimire 2013). During the National Biogas Programme, the Netherlands Development Organization and Heifer Project International (HPI), implemented domestic biogas projects in Cameroon. These organizations used an integrated approach to optimize institutional arrangements and to strengthen the capacities of all actors in the sector. During the NBP, farmers were provided subsidies and trained masons and farmers (to help them own biogas plants) (MINEE 2010). Nevertheless, farmers were expected to continue to adopt the technology after the programme. Some of the outcomes include the adoption of different sizes of biogas plants. Most of these biogas plants range from less than 1m^3 to 50m^{3,} depending on the purpose of building the biogas plant. Currently, less than one thousand rural biogas plants have been reported in Cameroon (Ndongsok et al. 2018). Despite the very low level of adoption of biogas technology, biogas remains a potential modern energy alternative in rural areas of Cameroon.

This study aims to investigate the behavioural factors influencing the choice of biogas plant size and pathways of sustaining small-scale biogas plants in rural areas of Cameroon. Furthermore, this paper seeks to position the COM-B model as a tool not only for understanding rural household behaviour towards biogas technology but also for predicting household potential size of biogas plants. The following research questions (RQs) were investigated to understand the factors influencing the choice of biogas plant size and the sustainability of biogas technology in rural areas of Cameroon.

RQ1: What are the factors influencing the choice of small-scale biogas plant size in rural households of Cameroon?

RQ2: What transition pathways can be deduced from the current behaviour (practices) to sustain household biogas production and use?

5.4. Materials and methods

5.4.1. Study area

This study was conducted in the North West and West Regions of Cameroon (Figure 5.1). In 2022, the rural populations of the North West and West regions were 1,087,395 and 987,486 inhabitants respectively (INS 2022). These regions are all located in the Western Highlands of Cameroon, characterized by high relief of elevations ranging from 1000 – 2500 m above sea level. This region is known for high rainfalls ranging from 1000mm to 2000mm per year, with a bimodal regime that allows savanna vegetation to thrive. This also provides favourable conditions for the cultivation of various crops such as irish and sweet potatoes, beans, plantains, cabbage, maize, banana, etc (Fews Net et al. 2019). The region has an average annual temperature of 20˚C which is favourable for both crop and animal production and natural psychrophilic or mesophilic biogas production. Both traditional and intensive livestock production are practiced in the region. Animals reared traditionally include cows, pigs, horses, goats and chickens. Intensive livestock production is mainly applied to pigs and poultry. Given the savanna vegetation, the population of this region cannot meet its cooking energy needs with fuelwood. This deficiency has attracted the attention of different actors to provide energy alternatives to meet household energy demand. The region was one of the hotspots of the National Biogas Programme (NBP) from 2009 to 2014 due to its suitability for biogas production based on fuelwood scarcity and widespread livestock production, amongst other factors.

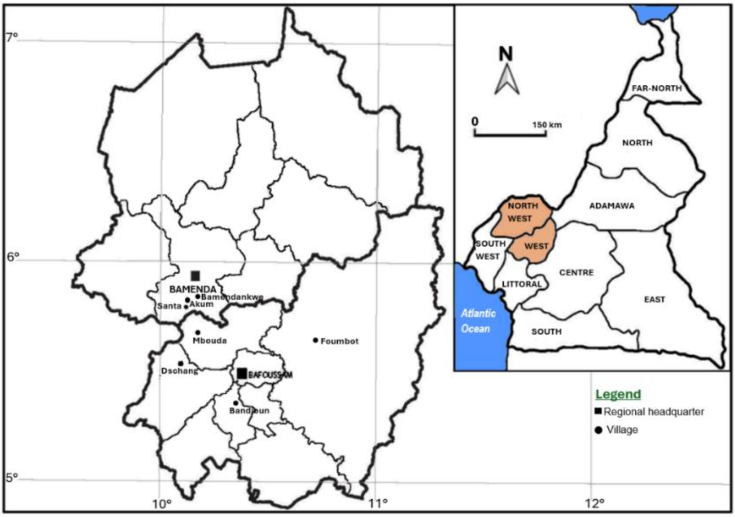


Table 5.1. Map of Cameroon showing the location of North West and West regions.

5.4.2. Sampling technique and identification of participants

The target population comprised rural households in the Western Highlands of Cameroon. This rural population is comprised mainly of subsistence farmers, small business owners (including farm businesses) and internally displaced persons (IDPs). The sample size used for this study was estimated using equation 5.1.

$$n = \frac{z^2pq}{e^2} \qquad (5.1)$$

Where n is the sample size, z is the value associated with 95% confidence interval (1.96), p is the proportion of the rural households (equal to 0.5 since the actual size is not known in all the population), q is 1-p and e is the margin of error (±5%).

With the application of equation 5.1, a sample size of at least 384 respondents was required for this study.

The stratified sampling method was used to identify the respondents for the study. The first stratum sought to include respondents from the two regions (North West and West). The second stratum was established to comprise users and non-users of biogas technology. However, there are few biogas plants in the regions. So, based on the expected sample size, it was planned to include at least 40 biogas users and 344 non-users of biogas technology in the sample. Finally, we randomly selected the respondents from both groups (users and non-users). This sampling approach enabled the identification of 35 users and 353 non-users of biogas technology in the study area. The locations where respondents were identified and their distribution is shown in Table 5.1. The distribution of the respondents per village differed due to ease of access. The higher the number of respondents per village, the easier it was to access them.

Table 5.2. Identification and distribution of respondents

Village	Non-biogas users	Biogas users
North West region		
Akum	57	4
Bamendankwe	48	6
Santa Mbei	48	6
Santo Njong	44	9
West region		
Bandjoun	56	4
Mbouda	34	1
Foumbot	21	2
Dschang	45	3
Total	388	

5.4.3. Variables and data collection

The outcome variable for this study is the choice of the different sizes of household biogas plants. The sizes of biogas plants are conceptualized in this study based on our previous assessment of the rural biogas plants in the study area. We classified the biogas plants into three sizes or categories: *i)* The biogas plants are owned by subsistence farming households, ranging from 4 to 10m^3 in size. These farmers rear a small number of animals mainly to sustain their livelihood. *ii)* The biogas plants, ranging from 15 to 30 m^3, are owned by a group of farmers practicing subsistence farming (shared biogas plant). These are owners of a community biogas plant where each concerned farmer brings organic waste to feed the biogas plant and collects biogas or digestate or both in return. The management of this biogas plant is similar to rural farm cooperative practice. *iii)* The biogas plants ranging from 20 to 50 m^3, often constructed in a small business animal farm. Such farmers own small business farms with about 15 cows or 50 pigs or more. The biogas produced is used to reduce the energy and fertilizer costs of the farm. The biogas produced can also be used for productive purposes such as food drying.

A literature review guided by the COM-B model led to the identification of explanatory variables related to the capability, opportunity and motivation of biogas users to choose among different types of biogas sizes of biogas plants. With this method, 29 aspects were identified to measure capability, opportunity and motivation, respectively. A validation of these aspects was done through an elicitation study with the farmers. This enabled the retention of 9 aspects which constitute the 9 variables used for measuring the capability, opportunity and motivation behaviour shaping the adoption of different sizes of biogas plants in rural areas of Cameroon. In addition, socio-economic data were collected to describe the target households and to identify their influence on the choice of a particular size of biogas plant. The descriptive statistics of the dependent and independent variables used in this study are shown in Table 5.2. A questionnaire survey was used to collect data for the variables retained for the study. The questionnaire was prepared in English and translated into French language. Data collection was done from March to May 2022. The questionnaire was administered in pidgin English in the North West region and French language in the West region. Those were the languages most spoken in each of the regions. The questionnaire was administered to each respondent face-to-face and lasted about 30 minutes. After the survey of each respondent, non-participant observation of each biogas plant was done to appraise the size and use of each biogas plant.

5.4.4. Data analysis

The cleaned Excel data was uploaded into the statistical software, STATA version 16.0 for analysis. A correlation test was performed to prevent multi-collinearity between the explanatory variables. The use of the MVP model was driven by the field observation of different forms of adoption of small-scale biogas plants in rural areas of Cameroon. That is, the farmers are choosing among different sizes of biogas plants, which are not mutually exclusive and correlated. For household i, choosing a biogas plant size, m, the multivariate probit model can be expressed as shown in equation 5.2.

$$y_{im}* = \beta_m' X_{im} + \varepsilon_{im} \qquad (5.2)$$

y_{im} = 1 if y_{im} > 0 and 0 otherwise (i= 1,2, ..., N; m = 1, 2, ..., M).*

Where y_{im} is the dependent variable. X_{im} is the combined effect of the explanatory variables, β_m is the matrix of simulated maximum likelihood (SML) parameters to be estimated, and ε_{im} is a vector of correlated error terms under the assumption of normal distribution, N is the number of the number of households, M is the number of biogas plant options.

The SML estimation of the MVP model was performed with the Geweke-Hajivassiliou-Keane (GHK) simulator developed by Cappellari and Jenkins (2003). The SML estimator is consistent as the number of observations and draws tends to infinity.

5.5. Results and discussions

5.5.1. Socio-economic characteristics of the rural households

The socio-economic characteristics of the respondents showed that the estimated mean age of rural household heads was 43.62 years. The household heads were dominantly men (95%). Only 5% of women-headed households. The monthly average rural household income was 75,600FCFA. However, the minimum monthly household income was as low as 27,000FCFA, pertaining to a subsistence household, while the maximum monthly income was 872,000FCFA, pertaining to a small rural business farm owner. The monthly household income had a standard deviation as high as 21,500FCFA, which partially justifies why the adoption of different sizes of biogas plants is evident in rural areas of Cameroon. A summary of the socio-economic data and those of other independent variables is shown in Table 5.2.

Table 5.3. Descriptive statistics

Variables	Measures	Mean	Std. dev.
Dependent variables			
Subsistence household biogas plant (4 - 10 m^3)	Dummy =1 if household choice of BGP is between 4 to 10m^3, 0 otherwise	0.77	0.43
Shared biogas plant (15 – 30m^3)	Dummy =1 if household is using a shared BGP, 0 otherwise	0.10	0.29
Small business farm biogas plant (20 – 50 m^3)	Dummy =1 if household has a biogas plant in small business farm, 0 otherwise	0.15	0.36
Socio-economic variables			
Age of household head	Continuous, age of household in years	43.62	9.29
Gender of household head	Dummy =1 if the household head is male, 0 otherwise	0.95	0.21
Household income	Continuous (FCFA)	150,42 2.80	21,500
Independent variables			
Capability			
Have experienced an awareness campaign about biogas technology	Dummy =1 if household head experienced awareness campaign about BGT, 0 otherwise	0.90	0.30
Have access to biogas masons	Dummy =1 if biogas user has access to biogas masons, 0 otherwise	0.57	0.50

Received training on the operation and maintenance of biogas technology	Dummy =1 if biogas user had training on BGT, 0 otherwise	1.24	0.67
Opportunity			
Have sufficient livestock to provide feedstock for the chosen size of BGP	Dummy =1 if household has sufficient feedstock for BGP, 0 otherwise	0.94	0.25
Have sufficient water to feed the biogas plant	Dummy =1 if household has sufficient water for BGP, 0 otherwise	0.98	0.13
Subsidy for the biogas plant	Dummy =1 if subsidy was used to build BGP, 0 otherwise	0.85	0.36
Motivation			
Biogas is clean energy	Dummy =1 if biogas is perceived as cleaner energy, 0 otherwise	0.95	0.22
Free organic fertilizer for crops and extra income	Dummy =1 if digestate is perceived as free organic fertilizer, 0 otherwise	0.92	0.27
Reduction of drudgery related to fuelwood collection	Dummy =1 if biogas reduces drudgery, 0 otherwise	0.98	1.23

A summary of the distribution of biogas users per size category of biogas plants is shown in Table 5.4. Most of the biogas plants belong to the first category of biogas plants (4 - 10m^3) and comprise 82.86% of the sample. The shared and small business biogas plants were 5.71% and 11.43% respectively. Most of the biogas plants are 'small domestic' because biogas technology has been promoted in these areas as a means to reduce poverty and enable access to modern energy for rural and vulnerable populations (MINEE 2010).

Table 5.4. Number and distribution of biogas plants identified

Type of biogas plant	Small domestic BGP (4 - 10 m^3)	Shared BGP (15 – 30m^3)	Small business farm BGP (20 – 50 m^3)	Total
Number of owners	29	2	4	35
Proportion (%)	82.86	5.71	11.43	100

5.5.2. Factors influencing household choice of biogas plants

Different biogas plant sizes are adopted in rural areas of Cameroon based on identified COM-B factors. The multivariate probit (MVP) regression results of these factors are shown in Table 5.5. The loglikelihood ratio or Wald test of the null hypothesis (H_0), ρ11=ρ12=ρ13=0, (where ρ1 is the small domestic BGP, ρ2 is the shared BGP, and ρ3 is the small business BGP), and X^2 (12) = 386.4; Prob >X^2 = 0.0000, indicating that the model fits the data correctly. The correlation (ρ) between the different sizes of the biogas plants is negative and significant, indicating that with the choice of one biogas plant size, it is less likely that the rural dweller will choose another size of BGP. This depends mainly on the capabilities, opportunities and motivation of the households to choose the BGP. The SML shows that the choice of one of the biogas plant sizes does not exclude the possibility of selecting another one. However, the chance of owning two sizes was estimated at 1.24%. This is partly accounted for by the high investment cost related to adopting a biogas plant.

Socio-economic factors influencing the choice of biogas plant size

The key socio-economic factors investigated in this study are age, gender and income of household head. In the case of shared and small business farm biogas plants, age was negatively correlated with the size of the biogas plant. The higher the age of the individual, the less likely the choice of biogas plant. Therefore, the age of the household head was not significant in selecting a particular size of biogas plant. Gender was not significant in making a choice of biogas plant. Gender has the highest influence on the choice of the small domestic biogas plant (31.8%), then 9.61% for the shared biogas plant and has the least influence on the small business biogas plant (2.2%). Household income is significant and negatively correlated to the small domestic biogas plant. Generally, low income is associated with small and shared plant adoption, while high income significantly increases the likelihood of choosing a small business biogas plant.

Table 5.5. Multivariate probit coefficient estimates of factors influencing choice of biogas plant

Variables	**Choice of biogas plant**		
	Small domestic BGP (4 - 10 m^3)	**Shared BGP (15 – 30m^3)**	**Small business farm BGP (20 – 50 m^3)**
	Coef. (se)	**Coef. (se)**	**Coef. (se)**
Socio-economic variables			
Age of household head	0.0024 (0.02)	-0.001 (0.01)	-0.006 (0.02)
Gender of household head	0.318 (0.09)	0.096 (0.06)	0.222 (0.08)
Household income	-0.260 (0.02)*	-0.100 (0.01)*	0.530 (0.02)***
Capability			
Have experienced an awareness campaign about biogas technology	0.237 (0.10)**	0.119 (0.06)***	0.117 (0.09)
Have access to biogas masons	0.029 (0.04)*	0.004 (0.02)**	0.025 (0.03)***
Received training on the operation and maintenance of biogas technology	0.083 (0.04)*	0.028 (0.02)**	0.111 (0.03)*
Opportunity			
Have sufficient livestock to provide feedstock for the chosen size of BGP	0.640 (0.11)**	-0.535 (0.07)***	0.105 (0.09)***
Have sufficient water to feed the biogas plant	0.401 (0.21)**	0.231 (0.13)**	0.169 (0.18)**

Subsidy for the biogas plant	0.541 (0.09)***	0.026 (0.05)***	0.514 (0.08)
Motivation			
Biogas is clean energy	-0.033 (0.11)**	0.037 (0.07)	0.034 (0.09)*
Free organic fertilizer for crops and extra income	0.737 (0.10)**	0.675 (0.06)***	0.057 (0.09)
Reduction of drudgery related to fuelwood collection	0.363 (0.16)**	-0.012 (0.10)*	0.350 (0.14)
Constant	-0.698 (0.32)	1.196(0.20)	0.501 (0.28)

Note: * 10% significance level; ** 5% significance level; *** 1% significance level.

The marginal effects of the factors influencing the choice of biogas plant size are presented in Table 5.6.

Table 5.6. Marginal effects of factors influencing choice of biogas plant size

Variables	**Choice of biogas plant**		
	Small domestic BGP (4 - 10 m^3)	**Shared BGP (15 – 30m^3)**	**Small business farm BGP (20 – 50 m^3)**
	Margin (se)	**Margin (se)**	**Margin (se)**
Socio-economic			
Age of household head	0.024 (0.02)	-0.0017 (0.01)	-0.006 (0.02)
Gender of household head	0.318 (0.09)	0.0961 (0.06)	0.022 (0.08)
Household income	-0.20 (0.02)*	0.040 (0.01)*	0.41 (0.02)***

Capability			
Have experienced an awareness campaign about biogas technology	0.237 (0.10)**	0.119 (0.06)***	0.117 (0.09)
Have access to biogas masons	0.004 (0.04)*	0.019 (0.02)**	0.025 (0.03)***
Received training on the operation and maintenance of biogas technology	0.083 (0.04)*	0.028 (0.02)**	0.111 (0.03)*
Opportunity			
Have sufficient livestock to provide feedstock for the chosen size of BGP	0.460 (0.11)**	-0.535 (0.07)***	0.150 (0.09)***
Have sufficient water to feed the biogas plant	-0.401 (0.21)**	0.231 (0.13)**	0.169 (0.18)**
Subsidy for the biogas plant	0.541 (0.09)***	0.514 (0.05)***	0.260(0.08)
Motivation			
Biogas is clean energy	-0.037 (0.11)**	0.033 (0.07)	0.30 (0.09)*
Free organic fertilizer for crops and extra income	0.033 (0.11)**	0.737 (0.06)***	0.057 (0.09)
Reduction of drudgery related to fuelwood collection	0.363 (0.16)**	-0.012 (0.10)*	0.350 (0.14)

Note: * 10% significance level; ** 5% significance level; *** 1% significance level.

Capability factors influencing the choice of biogas plant size

Having witnessed an awareness campaign about biogas technology has a positive correlation with household choice of biogas plants for all sizes. The marginal effects show that for every additional awareness experience gained, the chance for a subsistence household to adopt a small biogas plant will increase by 23.7% against 11.9% and 11.7% (least) for the shared and the small business farm biogas plants, respectively. Awareness is highly significant in influencing the choice of biogas plants. This indicates that awareness creation can contribute to influencing rural households to engage in biogas technology. Access to biogas masons is positively related to the choice of biogas plant size. The marginal effects show that the business farm biogas user is more likely to have access to a biogas mason than the shared and small domestic biogas plant users. This is evident with the percentage chance of 2.5% of small business farm biogas users to have a biogas mason against 0.4% and 1.9% chances of the small household and shared biogas users, respectively. This indicates that biogas masons are scarce in rural areas of Cameroon, especially for the small domestic biogas plants. According to the small household biogas users, the services of the biogas masons are usually expensive, reason why they are not able to afford them. The shared and business biogas plant users are more likely to pay for their services, thereby having more access to the masons. The training of a biogas user is positively related to the choice of size of a biogas plant. Training most significantly increases the chance of shared biogas users choosing the biogas plant over the domestic and small business farm biogas users.

Opportunities factors influencing the choice of biogas plant size

Sufficient livestock to produce feedstock to feed the biogas is positively and significantly correlated with the choice of biogas plant size. The sizing of the biogas plants depends on the availability of feedstock generated daily by a potential biogas user. The marginal effects show that for any increase in the quantity of feedstock generated, the small household is likely to adopt a biogas plant by 46% against 53.5% and 15% for the shared and small business farm biogas users. The availability of water is positively correlated with the choice of biogas plant size. The marginal effect shows that water availability will lead to a 40.1% increase in the chance to adopt a small domestic biogas plant against 23.1% and 16.9% for the shared and small business farm biogas plants, respectively. The availability of subsidies is positively correlated with the choice of biogas plant size. The availability of subsidy will lead to 54.1% in the choice of the small domestic biogas plant against 51.4% for the shared biogas plant. The subsidy was highly significant for these biogas plant sizes. This shows that most domestic and shared biogas plant users are more likely to choose their biogas plants if there are subsidies available for them. In the context of poverty and low-income areas, subsidies play a significant role in increasing the uptake of different sizes of biogas plants. The subsidy was not significant in the case of the small business farm biogas plant. According to these biogas users, subsidies would increase the opportunity of a small business farmer by 26% to select their corresponding biogas plant size. According to these small business farmers, their biogas plants were fully constructed without subsidy.

Motivation factors influencing choice of biogas plant size

The perception of biogas as cleaner energy is positively correlated with the choice of biogas plant size. While the intention of adopting biogas technology is to reduce indoor pollution and sanitation due to smoke and burning of fuelwood, the perception of biogas as a clean energy source will lead to an increase in 3.7% chance of choosing the small domestic biogas plant against 3.3% and 30% for the shared and business biogas plants respectively. Biogas is generally a cleaner alternative to traditional energy sources such as fuelwood and charcoal in rural households (Kabeyi & Oludolapo 2022). In the small business farm, biogas is not only used for cooking but also for heating the animals and lighting in some cases. In such cases, biogas is not only perceived as a clean energy source, but also as a cheaper source of energy for the farm and household. This contributes to reducing energy costs of production and household energy expenditure. The small business farm biogas owners were more willing to pay for the biogas plants than the other users due to the higher benefits they get. Small business farm owners are more likely to select their biogas plants due to the energy needs of their farms. The perception of biogas technology as a source of organic fertilizer is positively associated with the choice of biogas plant. A higher significance is seen with the shared biogas plant, followed by the small household biogas plant. The perceived increase in the perception of biogas technology as a source of organic fertilizer leads to a 73.7% chance of choosing the small domestic biogas plant, against a 67.5% and 57% chance of selecting the shared and small business farm biogas, respectively. The perception of biogas technology as a means to reduce drudgery in fuelwood collection is positively related to the choice of biogas plant.

5.5.3. Discussion

The results of this study show a clear divide based on income levels. Lower-income households tend to adopt smaller domestic BGPs, while higher-income households prefer small business BGPs. This finding is consistent with numerous studies on biogas energy adoption. Studies by Walekhwa et al. (2009) and Mwirigi et al. (2009) emphasize that household income is a significant determinant of biogas adoption, as well as in the selection of the size of a biogas plant. Both studies found that higher-income households are more likely to choose the small business BGP or more efficient BGPs because they can afford the initial capital investment. The higher probability of adopting small domestic BGP by low-income households in the current study is consistent with this, as lower-income households often cannot afford the higher upfront costs of larger biogas plants. Another research by Gebreegziabher et al. (2014) highlights that financial support, like subsidies and access to credit, significantly improves the likelihood of biogas adoption among low-income households. This aligns with the current study's finding that subsidies positively influence the adoption of both small domestic and small business BGPs, underscoring the need for financial assistance in promoting biogas technology among less affluent households.

The results show that male-headed households are more likely to adopt biogas plants, especially small domestic and business BGPs. This finding resonates with other studies examining gender dynamics in energy adoption. Köhlin et al. (2011) found that male-headed households often have more decision-making power and economic resources, which enables them to adopt cleaner technologies like biogas. This may be due to traditional gender roles in many developing countries, where men control household finances and investment decisions. Conversely, research by Clancy et al. (2012) highlights that female-headed households tend to have less access to capital and may face more barriers in adopting technologies like biogas. This justifies the importance of gender-sensitive policies to ensure that female-headed households are not left behind in the transition to cleaner energy technologies.

The positive effect of awareness campaigns on biogas adoption across all sizes of biogas plants in this study aligns with findings from other studies emphasizing the role of information dissemination. Studies such as Mwirigi et al. (2009) and Khan and Martin (2016) emphasize the importance of awareness programs in increasing the adoption of biogas technology. These studies found that households that are better informed about the benefits of biogas are more likely to adopt it. The significant effect of training on biogas maintenance in the current study also supports findings that technical knowledge is a key enabler of sustained use, as noted by Walekhwa et al. (2009). Similarly, Adhikari et al. (2020) found that educational and awareness campaigns significantly boost the adoption rates of small biogas plants in rural Nepal, as awareness reduces uncertainty about the technology and provides assurance about its reliability and utility.

This study found that having sufficient livestock and access to water were critical factors in choosing the size of biogas plants. This result has been documented in various studies. Mwirigi et al. (2014) emphasize that access to sufficient livestock is crucial for biogas adoption, especially in regions where animal manure is the primary feedstock. These studies found that households with higher availability of feedstock (more livestock) are significantly more likely to adopt BGPs, particularly small BGPs that require moderate amounts of feedstock. Similarly, Parawira (2009) reported that lack of water is a key constraint in biogas plant adoption. Households in regions with water scarcity are less likely to adopt biogas plants, as the BGPs require significant amounts of water to process the feedstock. The positive coefficient for water availability in the current study reinforces the importance of ensuring reliable water access to facilitate the adoption of biogas technology.

The strong effect of subsidies in promoting the adoption of small and large biogas plants found in this study is consistent with several other studies. Studies such as Walekhwa et al. (2009) and Mailu et al. 2018 highlight that subsidies are often critical in reducing the financial burden of biogas technology installation, particularly for low-income households. Subsidies help overcome the high initial costs, which are frequently cited as a major barrier to biogas adoption. These studies, along with the current findings, emphasize the importance of government support programs in scaling up biogas technology in rural areas of Cameroon. Research by Qadir et al. (2021) also supports the need for targeted subsidies that consider the income levels and financial constraints of households. They suggest that subsidies should be designed not only to reduce upfront costs but also provide longer-term support, such as through maintenance training or post-installation services, to ensure the sustainable use of biogas plants.

5.5.4. Pathways to adopting biogas technology in rural areas of Cameroon

Based on the understanding of the choices of the different sizes of biogas plants and the adoption behaviour of biogas users in rural areas of Cameroon, three normative pathways of sustaining biogas technology in rural areas of Cameroon can be deduced. The uptake of different sizes of biogas plants in rural areas of Cameroon was influenced mostly by the opportunities they had to choose the size of a biogas plant for their household. Based on this study, the identified normative pathways to adopt biogas technology in rural areas of Cameroon include:

- *Pathway based on the productive-consumptive use of biogas*

Based on this study, this pathway corresponds to the construction of a biogas plant in a small business livestock farm or for food processing. This implies that considering the biogas plant as a component of a small business animal farm provides a suitable opportunity for long-term biogas production and use. These biogas plants often range from 20 to 50 m^3. The productive use of biogas will enhance the economic viability, sustainability, and broader impact of biogas technology.

- *Pathway based on cost-sharing*

Cost-sharing lowers the financial burden on the households to own a biogas plant. By distributing the cost of the biogas plant across many households or farmers, cost-sharing reduces the direct financial burden on each of them. Cost sharing also distributes the financial risk between the different users of the shared biogas plant. This reduces the financial pressure on a single household or farmer. Cost sharing might reduce the reliance on external donors or government funding. By requiring local or individual contributions, cost-sharing can increase the financial resilience of biogas projects.

- *Pathway based on the empowerment of the vulnerable population to adopt biogas technology*

Empowering vulnerable populations or households to adopt biogas technology involves providing them with the necessary resources, knowledge, and support systems to utilize their biogas plant (sustainable energy solution) effectively. Vulnerable populations, such as low-income households, rural communities, and marginalized groups, often face barriers like lack of financial resources, education, and access to technology. Addressing these challenges can lead to significant social, economic, and environmental benefits for these groups while also fostering broader adoption of renewable energy technologies. This study identified that most of the biogas plants in the study area received subsidies and capacity building to adopt the technology.

A SWOT analysis of the different pathways of sustaining biogas technology is shown in Table 5.7.

5.6. Conclusion

Behavioural factors influence the choice of the appropriate size of a biogas plant in a rural setting. These factors also influence the level of achievement of positive impacts on the user households and the sustainability of the technology. The factors influencing the choice of small-scale biogas plant size are divided into three categories including capability, opportunity and motivation. The interaction between these factors is vital for understanding and influencing behaviour change. This study explored the factors influencing the choice of small-scale biogas plant size in rural households in Cameroon.

Table 5.7. SWOT comparison of the different pathways to adopt and sustain small-scale biogas technology in rural areas of Cameroon

Pathway / SWOT	Productive use	Cost-sharing	Empowerment
Strengths	- Income generation - Energy security - Environmental benefits - Potential for job creation	- Shared costs - Community ownership - Economies of scale - Sustainability	- Social inclusion - Health benefits - Livelihood enhancement - Sustainable development
Weaknesses	- High initial investment - Technical expertise - Dependence on feedstock	- Coordination issues - Limited scalability - Maintenance responsibility	- Limited financial capacity - Technical barriers - Small-scale impact
Opportunities	- Rural industrialization - Funding availability - Climate finance	- Government or NGO support - Community development	- Empowerment programs - Community resilience - Public health and environmental support
Threats	- Market risks - Competition with fossil fuels - Feedstock shortage	- Dependency on group cooperation - Inconsistent usage - Policy or regulatory risks	- Sustainability concerns - Dependence on external funding - Cultural or social resistance

The capability in decision making to choose a specific size of biogas plant is influenced by household income, awareness campaigns, access to biogas masons and training on the operation and maintenance of biogas plants. The opportunity for rural households to choose a biogas plant is linked with the availability of feedstock, sufficient water, and subsidies. The rural households were motivated by perceiving the biogas plants as a source of clean energy, organic fertilizer, extra income, and a means to reduce the drudgery in fuelwood collection. Based on our findings, three normative behavioural pathways of choice for biogas plants have emerged in rural areas of Cameroon. The three pathways include productive-consumptive use, cost-sharing and empowering vulnerable rural households to adopt biogas technology. The productive-consumptive use pathway is identified in rural areas as the households owning a small animal farm and a small-scale biogas plant that meets the energy needs of their farms and households. The pathway based on cost-sharing is reflected by joint ownership of the biogas plant, where the investment cost, benefits and risks are distributed between many households. This reduces the financial burden during the installation and maintenance of the biogas plant. The final pathway involves empowering vulnerable households to adopt small household biogas plants less than or equal to $10m^3$ in size. This pathway often depends on external and government funding. This study suggests that efforts to promote bioenergy transition in rural areas of Cameroon should promote farm entrepreneurship, integrating biogas technology. While cost-sharing is considered a means to share the burden of the uptake of biogas technology, the resource-poor or vulnerable population need to be empowered to adopt biogas technology for equitable access to clean energy.

References

Adhikari NP, Adhikari RC. 2020. Analysis of biogas production potential based on livestock dung availability: A case of household biogas plants in Nepal. Biofuels 13(2):1-9. doi: 10.1080/17597269.2021.1899363.

Cappellari L, Jenkins SP. 2003. Multivariate Probit regression using simulated maximum likelihood. The Stata Journal, 3(3), 278–294. doi: 10.1177/1536867X0300300305.

Clancy J, Winther T, Matinga M, Oparaocha S. 2012. Gender equity in access to and benefits from modern energy and improved energy technologies world development report background paper.

Faul F, Erdfelder E, Buchner A, Lang A. 2009. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behavior Research Methods 41, 1149–1160. doi: 10.3758/BRM.41.4.1149.

Fews Net, MINADER, USAID. 2019. Livelihood zone map and descriptions for Cameroon. A report of the famine early warning systems network. Available from https://fews.net/sites/default/files/documents/reports/Cameroon%20LH_Zoning_Report_201911_Final.pdf (accessed on 12 May 2024).

Fulford D. 2015. Small-scale, rural biogas programmes, Rugby, UK: Practical Action Publishing. Doi: 10.3362/9781780448497.

Gebreegziabher Z, Naik L, Melamu R, Babulo BB. 2014. Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa. Biomass and Bioenergy, 70, 130 – 140. Doi: doi: 10.1016/j.biombioe.2014.02.036.

Horta A, Wilhite H, Schmidt L, Bartiaux F. 2014. Socio-Technical and Cultural Approaches to Energy Consumption. An Introduction. Nature and culture. doi: 10.3167/nc.2014.090201.

IEA, IRENA, UNSD, World Bank, WHO. (2023). Tracking SDG 7: the Energy Progress Report, World Bank, Washington DC. Available from https://data.worldbank.org/indicator/EG.ELC.RNWX.ZS?locations=CM. (accessed 10 July 2024).

IEA, IRENA, UNSD, World Bank, WHO. (2024). Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC.

INS. 2022. National Institute of Statistics of Cameroon Statistical. Yearbook for the North West Region – 2022 Edition. Available from https://ins-cameroun.cm/wp-content/uploads/2024/05/STATISTICAL-YEARBOOK-ed-2022-NW_Final.pdf (accessed on 2 March 2024).

Jürisoo M, Lambe F, Osborne M. 2018. Beyond buying: The application of service design methodology to understand adoption of clean cookstoves in Kenya and Zambia. Energy Research & Social Science, 39, 164-176. doi: 10.1016/j.erss.2017.11.023.

Kabeyi MJB, Oludolapo AO. 2022. Biogas Production and Applications in the Sustainable Energy Transition. Journal of Energy. doi: 10.1155/2022/8750221.

Kang H. 2021. Sample size determination and power analysis using the G*Power software. J Educ Eval Health Prof 18:17. doi: 10.3352/jeehp.2021.18.17.

Keller M, Noorkõiv M, Vihalemm T. 2022. Systems and practices: Reviewing intervention points for transformative socio-technical change. Energy Research & Social Science, 88, 102608. doi: 10.1016/j.erss.2022.102608.

Ketuama CT, Mazancova J, Roubík H. 2022. Impact of market constraints on the development of small-scale biogas technology in Sub-Saharan Africa: a systematic review, Environ. Sci. Pollut. Res. 29 65978–65992. doi : 10.1007/s11356-022-22262-y.

Khan EU, Martin AR. 2016. Review of biogas digester technology in rural Bangladesh. Renewable and Sustainable Energy Reviews, 62, 247-259. doi: 10.1016/j.rser.2016.04.044.

Köhlin G, Sills EO, Pattanayak SK, Wilfong C. 2011. Energy, Gender and Development. Policy Research Working Paper, No. WPS 5800. Washington, DC:Social Dimensions of Climate Change Division, World Bank.

Mbah M, Franz A. 2021. Revitalization and branding of rural communities in Cameroon using a circular approach for sustainable development—A proposal for the Batibo Municipality. Sustainability, 13(12), 6908. doi: 10.3390/su13126908.

Michie S, van Stralen MM, West R. 2011. The behaviour change wheel: A new method for characterising and designing behaviour change interventions. Implementation Sci 6, 42. doi: 10.1186/1748-5908-6-42.

Mukisa PJ, Ketuama CT, Roubík H. 2022. Biogas in Uganda and the Sustainable Development Goals: A Comparative Cross-Sectional Fuel Analysis of Biogas and Firewood. Agriculture, 12(9), 1482. doi: 10.3390/agriculture12091482.

Mundaca L, Zhu X, Hackenfort M. 2022. Behavioural insights for sustainable energy use. Energy Policy, 171, 113292. doi: 10.1016/j.enpol.2022.113292.

Mwirigi JW, Makenzi PM, Ochola WO. 2009. Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. Energy Sustain Dev 13:106–115. doi: 10.1016/j.esd.2009.05.002.

Obaideen K, Abdelkareem MA, Wilberforce T, Elsaid K, Sayed ET, Maghrabie HM, Olabi AG. 2022. Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines. Journal of the Taiwan Institute of Chemical Engineers 131, 104207. doi: 10.1016/j.jtice.2022.104207.

O'Connell KA, Devine J. 2015. Who is likely to own a latrine in rural areas? Findings from formative research studies. Waterlines, 34, 314-329.

Parawira W. 2009. Biogas technology in sub-Saharan Africa: status, prospects and constraints. *Rev Environ Sci Biotechnol* 8, 187–200. doi : 10.1007/s11157-009-9148-0.

Qadir SA, Al-Motairi H, Tahir F, Al-Fagih L. 2021. Incentives and strategies for financing the renewable energy transition: A review. Energy Reports, 7, 3590-3606. doi: 10.1016/j.egyr.2021.06.041.

Ritzer G, Jurgenson N. 2010. Production, Consumption, Prosumption: The nature of capitalism in the age of the digital ‘prosumer’. *Journal of Consumer Culture*, *10*(1), 13-36. doi: 10.1177/1469540509354673.

Trotsenburg A. 2023. Breaking Down Barriers to Clean Energy Transition. World Bank. Available from https://www.worldbank.org/en/news/feature/2023/05/16/breaking-down-barriers-to-clean-energy-transition#:~:text=Developing%20countries%20face%20a%20triple%20penalty%20when%20transitioning,projects%2C%20and%20are%20locked%20into%20fossil%20fuel%20dependency (accessed on 12 July 2024).

Walekhwa PN, Mugisha J, Drake L. 2009. Biogas energy from family-sized digesters in Uganda: critical factors and policy implications. Energy Policy 37:2754–2762. https://doi.org/10.1016/j. enpol.2009.03.018.

World Bank. 2018. Access to Energy is at the Heart of Development. Available from https://www.worldbank.org/en/news/feature/2018/04/18/access-energy-sustainable-development-goal-7#:~:text=Lack%20of%20sufficient%20power%20generation%20capacity%2C%20poor%20transmission,among%20the%20biggest%20hurdles%20for%20extending%20grid-based%20electricity (accessed on 12 June 2024).

6. Exploring the causes of slow biogas energy transition in rural areas of Cameroon: A technological innovation systems approach

Adapted from Ketuama CT, Roubík H. 2025. Exploring the causes of slow biogas energy transition in rural areas of Cameroon: A technological innovation systems approach. Renewable Energy 241, 122269. doi: 10.1016/j.renene.2024.122269.

Contributions

Hynek Roubík and Chama Theodore Ketuama conceived the idea for the paper. Chama Theodore Ketuama collected, analysed the data and wrote the original manuscript. Revisions were done by Chama Theodore Ketuama and Hynek Roubík. Supervision was done by Hynek Roubík.

Abstract

The diffusion of biogas technology remains extremely slow in Cameroon despite global mobilisation to transition to cleaner energy sources. Without adequate evidence to inform the formulation of new policies and strategies to revamp the biogas sector, this study applies a technological innovations systems (TIS) approach to investigate the causes of the slow transition to biogas energy in rural areas of Cameroon. This included identifying the structural/functional problems, performance analysis of the biogas innovation system (BIS) and the systemic problems hindering the development and diffusion of biogas technology in Cameroon. With a qualitative case study approach, primary and secondary data collected through document study, 92 interviews, and direct observation of 51 biogas plants were used. The results reveal a very weak but emergent biogas innovation system. This is caused by combined structural and dynamic (systemic) problems resulting mainly from a poor institutional setting, lack of legitimacy, weak biogas actor-network, inadequate funding and technical capacity to sustain the technology. Building a resilient biogas market in Cameroon requires providing solutions to the current systemic problems.

Keywords: Sustainability transitions, biogas technology, clean cooking, innovation systems, bioenergy policy, Cameroon.

6.1. Introduction

Developing innovation capabilities and sustaining small-scale biogas systems in developing countries continues to be a major challenge to enabling access to clean energy for all. Biogas is clean energy produced through the anaerobic digestion of organic waste from plant, animal origin and sewage sludge using biogas plants. Biogas is mainly comprised of approximately 50 - 70% methane (CH_4) and 30 - 50% carbon dioxide (CO_2). Biogas systems play a significant role in sustainability transitions by combining energy production, waste management, fertilizer (bio-slurry) production and healthier indoor environment at the local household level and reducing greenhouse gas (GHG) emissions at the global level (Kabeyi & Oludolapo 2022). Biogas systems contribute to achieving the goals of the 2030 Agenda, directly sustainable development goal (SDG) 7 and indirectly 11 others (Obaideen et al. 2022). Biogas technology is different from other sustainable technologies in that it is deeply embedded in local institutional structures and social practices (Bluemling et al.

2013). Hence, the adoption and dissemination of biogas technology are societal challenges.

Since the introduction of biogas technology in Cameroon in 1979 (Steedman 1979, less than 1000 domestic biogas plants have been constructed in peri-urban and rural areas despite the enormous potential of household, agricultural and livestock waste (Ndongsok et al. 2018). Biogas literature suggests that the causes of the failure of biogas technology in developing countries include but not limited to low-income levels affecting the technology affordability, lack of awareness, lack of human skills or technological capabilities, low institutional support, and lack of regulations impeding entrepreneurship (Kabeyi & Oludolapo 2022; Qudrat-Ullah 2024; Ketuama et al. 2022). (Kalina et al. 2022) stated that the African continent has not met expectations in developing the biogas sector. The failure of biogas technology has been reported in several African countries, including Tanzania (Hewitt et al. 2022), Uganda (Kalina et al. 2022), and Senegal (Diouf & Miezan 2019). By 2019, the number of Africans cooking with biogas was 410000, representing less than 0.5% of the continent's biogas potential (IRENA 2017).

This study recognises that the problems hindering biogas technology's development and rapid diffusion are systemic, rather than isolated (individual problems). To this effect, the technological innovation systems (TIS) framework is helpful to explore the causes of the slow transition to small-scale biogas technology in Cameroon. The TIS framework has often been used to understand the dynamics of an innovation system around a specific technology, identify shortcomings and derive recommendations for the design of policies supporting the technology. The TIS framework has been prominently applied in recent years to analyse emerging technologies in sectors such as energy, transportation, or water (Markard et al. 2015). Following criticisms of the TIS framework, the operationalisation of the framework in developing countries was enabled by Edsand (2019), with the extension of the TIS functions based on the landscape factors (exogenous or contextual) of the multi-level perspective (MLP) that can further influence innovation systems in developing countries.

To understand the causes of the slow transition to small-scale biogas plants in Cameroon using the TIS framework, the following research questions have been formulated: How have the structural and functional elements of the biogas innovation system evolved from 1979 to 2022? What are the structural and functional problems hindering the development of the biogas innovation system in Cameroon? What are the systemic problems hindering the development of Cameroon's biogas innovation system? Responding to these questions will enable the identification of the policy recommendations to build a better biogas technological innovation system as well as improve future biogas energy transition initiatives or interventions in rural areas of Cameroon. This article adds to the knowledge on applying the TIS approach to understand the evolution and problems of energy systems in developing countries. It also provides more knowledge on the status of biogas technology transition and policy recommendations to improve future transition to biogas technology in rural areas of Cameroon. This study focuses on substituting traditional fuels such as firewood and charcoal with biogas from agriculture and livestock waste. In this study, only small-scale domestic or biogas plants are considered. Medium and large-scale biogas plants are excluded.

6.2. Theoretical framework: TIS analysis

Transition and TIS studies emerged from evolutionary economics (Nelson & Winter 1982), innovation systems (Lundvall et al. 2002), and the social construction of technology (Bijker et al. 1987). The TIS approach is useful in understanding, from a systems perspective, the structures and processes influencing the propagation of a particular technology. At the national level, the biogas innovation system consists of all actors, institutions, and policies influencing biogas production and use. The small-scale BIS is part of the wider national BIS, which is part of the BIS. With emphasis on energy production and use in this study, the national energy innovation system is part of the global energy innovation system. The TIS framework analyses technological systems in two main parts, the structural and functional components (Edsand 2019).

The structural analysis is focused on the actors, networks, institutions, and technology (Bergek 2008). Knowledge of the relevant actor groups (Pinch & Bijker 1984) reveals the socio-technical dynamics of the development of a technology. The composition and alignment of the network of actors lead to the failure or success of the innovation system. Actor networks sustain development, attract resources and new actors, enable learning, and carry expectations (Van der Laak et al. 2007). The institutional context is defined as the cognitive, regulative, and normative rules that enable and constrain actor behaviour (e.g. policies, laws, technology regulations, routines, markets, culture).

The functions of an innovation system represent the key activities that influence its functioning (Negro et al. 2007). These functions of the innovation system focus on the dynamics of what is ‘achieved’ in the system rather than on the dynamics in terms of structural components only (Bergek 2008). Hence its transition dynamics. There exist seven main functions of innovation systems (Bergek 2008; Hekkert et al. 2007). The first function, entrepreneurial activities (*F1*) include all actions that entrepreneurs take to “turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.” (Hekkert et al. 2007). The second function, knowledge development (*F2*) or learning includes all activities where learning occurs. It includes ‘learning by searching’ and ‘learning by doing’ (know-how). The third function, knowledge diffusion (*F3*), encompasses the exchange of information within and between networks. “The function captures the breadth and depth of the knowledge and how that knowledge is diffused and combined in the system” (Jacobsson 2008). It includes ‘learning by interacting’ and ‘learning by using’. The is related for example to networks between users and producers. The fourth function, guidance of the search (F*4*), Guidance of the search describes all activities “that can positively affect the visibility and clarity of specific wants among technology users.” (Hekkert et al. 2007). It comprises policy goals, but also expectations by the public or statements of opinion leaders. The fifth function, market formation (*F5*), includes all activities that take place to form a market for the technology. Such activities can be taken by e.g. governments through the implementation of a favourable tax regime but also by other agents in the innovation system. The sixth function, resource mobilization (*F6*), describes activities which are undertaken to access and secure human, financial, and natural resources. The seventh function, creation of legitimacy (*F7*), includes all activities that are undertaken to increase the acceptance of a technology. This can, for example, be important in the case where an incumbent regime has to be overcome.

Literature (Table 6.1) suggests that the TIS framework has been used in developing economies to understand the diffusion of sustainable technologies such as small wind, solar photovoltaic, electric mini-grids and biogas systems. All these studies focused on understanding the emergence of innovation systems for specific energy technologies in the respective nations. In Kenya the TIS was used to assess the presence and the functional strength of the small wind innovation system (Wandera 2020). In Rwanda and Kenya, the studies analysed the biodigestion innovation system's functional strengths, weaknesses and blockages (Tigabu et al. 2015a; Tigabu et al. 2015b). In Ethiopia, it enabled the understanding of the functional build-up of solar photovoltaic innovation system (Kebede & Mitsufuji 2016). In Laos, the study analysed the structural and functional remote mini-grids innovation system. In Brazil, the TIS framework was used to assess the perceptions of actors on the functions of the biogas innovation system. The TIS framework has been useful to improve country-specific knowledge on the building innovation systems for renewable energy technologies. The application of TIS framework in the Cameroon has not only focused on the emergence of the biogas innovation system but also extends the analysis of the systemic problems in a developing country.

Table 6.1. Some studies on TIS analysis of energy systems in developing countries

Country	Application	References
Kenya	Small-scale wind energy	Wandera (2020)
Rwanda and Kenya	Small-scale biogas	Tigabu et al. (2015a) Tigabu et al. (2015b)
Ethiopia	Solar photovoltaic	Kebede and Mitsufuji (2016)
Brazil	Biogas	Borges et al. (2023)
Laos	Remote electric mini-grids	Blum et al. (2015)

A key characteristic of the TIS approach is that it analyses the performance, growth and decline of a technology in terms of the actors, institutions and networks (Koirala 2018). Therefore, the TIS framework is often considered as myopic (inward-looking) and neglecting the external environment of the technology (Edsand 2019). These criticisms were addressed by Edsand (2019) and Markard and Truffer (2008). Similar to the TIS framework is the MLP which suggests that technological transitions occur through the interactions of three different levels: niche, regime and landscape. Both TIS and MLP frameworks are complementary, but the TIS approach provides more insights into a specific technology's dynamics which is influenced by wider technological landscape factors and regimes. The strategic niche management (SNM) framework is limited on the niche level of the MLP highlighting the need for protective spaces and user engagement in early stage of technology development.

The slow transition to renewable energy is often caused by systemic problems or failure or imperfections or weaknesses.

Systemic problems can be defined as all systemic factors that block the operation and the development of innovation systems (Negro et al. 2012). Some of the systemic problems hindering the development of innovation systems and not limited to developed countries include market structure, institutional (hard and soft), infrastructure (physical and knowledge), interaction (too strong and too weak) and capability problems (Negro et al. 2012; Wieczorek & Hekkert 2012).

6.3. Description of the Cameroon's biogas case study

This study focuses on identifying the causes of the slow transition to biogas energy consumption, especially in peri-urban and rural households of Cameron. Cameroon is a lower-middle income county located between latitude 1° and 13° North and longitude 8° East (map shown in Figure 6.1). In 2022, the population of Cameroon stood at 27.91 million. This year, an estimated 41.27% (equivalent to 11,520,330 inhabitants) of the total population of Cameroon lived in rural areas (World Bank 2022).

In 2022, 94% of the urban population had access to electricity against 25% in rural areas (World Bank 2022). Some of the reasons that account for the low electricity access in rural areas include the limited electricity grid that cannot reach some rural areas; high cost of infrastructure, corruption, poor coordination, and hydrological challenges that affect electricity production (Bijker et al. 1987). The major renewable energy sources in Cameron include solar, wind, geothermal and biomass (Kidmo et al. 2021). Despite the availability of these energy sources, the cost of accessing them is still very high and not affordable to rural dwellers (Aziz 2020). In rural areas, modern energy sources such as liquefied petroleum gas (LPG) and electricity are scarce, leading to high dependence on firewood and kerosene for cooking and lighting respectively. The data collected in 2018 showed that 96.3% of the rural population mainly uses firewood for cooking (Rubinstein et al. 2021). Most of the rural is engage in crop and animal production, generating organic waste that is usually not used. Biogas experimentation in the country began since 1979 in attempts to valorise the free organic waste resource (MINEE 2010). The Netherlands Development Organisation (SNV) estimated that waste generated in Cameroon has the potential to feed 284000 to 724000 household biogas plants (SNV 2018). Less than 1% of this biogas potential has been mobilised due to several constraints. Small-scale biogas plants in Cameroon are exploited to provide decentralised clean energy for cooking, lighting, and fertilizer (bio-slurry). The development of renewable energy (including biogas) in Cameroon faces several bottlenecks in policies, regulations, institutions, knowledge diffusion, technical capabilities; and financial support. At the farm-level, farmers cannot afford the high cost of the biogas plants (Muh et al. 2018). This is because the rural population of Cameroon is predominantly comprised of smallholder farmers engaged in crop, livestock production and other small businesses to sustain their livelihoods. Despite these activities, 56.8% of this rural population is considered to be facing poverty (Knoema 2023). This poverty is caused by low crop yields, inadequate use of farm inputs, animal diseases, and poor rural infrastructure, leading to the farmers' inability to acquire the biogas plants. Most of the reported biogas plants in Cameroon have total volumetric capacities ranging from 1 to 50m^3. Most biogas plants are constructed with masonry materials. The masonry CM2013 model, which is similar to the fixed dome model, is locally adapted to the Cameroonian climatic conditions (MINEE 2010). These biogas plants are buried in the ground to provide adequate temperature for mesophilic operation. Other types of biogas plants available in the country are made from plastic and reinforced fiberglass materials. Some of the plastic biogas plants are imported, while others are fabricated from locally plastic tanks. The reinforced fiberglass biogas plants are the least common in the country.

To improve access to these sustainable technologies, Cameroon has planned in its Nationally Determined Contribution (NDC) by 2035 (2010 baseline) to increase by 25% the renewable energy share in the power generation mix (excluding large hydroelectricity) and a 32% reduction of greenhouse gas emissions (UNFCCC 2021). This includes a 10% substitution of firewood with biogas by 2030. This measure is still largely insufficient. Therefore, knowledge of the causes of the slow biogas energy transition will contribute to developing new policies, interventions, strategies, etc to overcome the development problems. In 2022, the World Intellectual Property Organisation (WIPO) was ranked Cameroon 121st among the 132 countries in the global innovation index by the (WIPO 2023). The global innovation index considers factors like political environment, education, infrastructure, and knowledge creation.

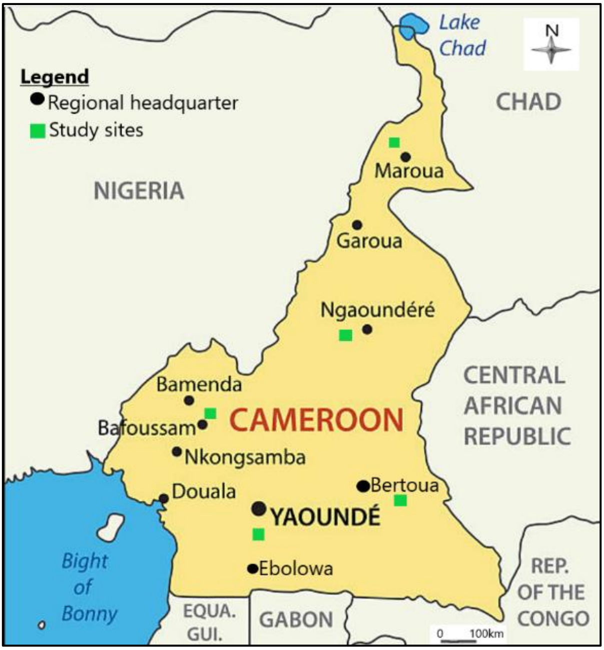


Figure 6.1. Map of Cameroon showing study sites

6.4. Methods

This study is focused on analysing the structural and functional elements of the biogas TIS to identify the problems causing slow biogas energy transition. To this effect, a qualitative case study (Yin 2018) was used to collect and analyse evidence from the small-scale biogas sector. The time horizon considered for this study is from 1979 to 2022. Event History Analysis (EHA) was used to understand the occurrence of functional problems over time, identifying their causes (Yamaguchi 1991). EHA is a process approach that traces evolutionary dynamics by examining the sequence of events. Events are key points in time that influence the system or reveal important characteristics.

Expert elicitation was used to assess the impact of the functional problems on the evolution of the biogas innovation system. Field data collection was carried out from December 2020 to May 2021 and November 2022 in English and French languages. The French data were translated into English before analysis. The data collection methods used were in the following order, document analysis, interview of respondents and field observation of biogas technology problems. Literature review was conducted till December 2023. Document analysis contributed to the understanding of the structural elements of the Cameroon's biogas innovation system. This enabled the acquisition of information about the actors, networks, institutions and process of the small-scale biogas sector in Cameroon. Document analysis was carried out on grey and peer-reviewed literature of biogas information from 1979 to 2022, corresponding to the period from the first Cameroon's government-led initiative to diffuse biogas technology up till 2022. Grey literature collected included publications on the installation of biogas plants, the National Biogas Programme (NBP), situation reports on renewable energy, regulatory framework, and the energy transition in Cameroon. Grey literature and peer-reviewed documents were collected through a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Nightingale 2009). Documents were searched from google, Web of Science and SCOPUS databases. Keywords such as 'biogas Cameroon', 'biogaz Cameroun', biogas actors Cameroon', and 'acteurs biogaz Cameroun' were used. Using the PRISMA protocol, 12 and 3 peer-reviewed articles were retrieved from SCOPUS and Web of Science respectively. Grey literature comprised of 11 documents were retrieved from google while 3 documents were collected by the authors from the Sub-directorate of Renewable Energy at the Ministry of Water and Energy Resources, Cameroon. In total, 29 documents were collected for the study. Interviews were conducted to understand the functioning of the biogas TIS. An interview guide was used during the interviews. These interviews were face-to-face and administered to different actors of the biogas sector in Cameroon, divided into expert organisations, key informants and farmers or potential consumers or users of biogas including men and women. The experts and key informants were purposively sampled after document analysis. The main criteria used to select the respondents were their previous and current engagement in actions related to the development of biogas technology in Cameroon. Snowball sampling was used to identify the biogas users/farmers. (Table 6.2). Once the first biogas user was identified, contact details of the next respondent were collected and subsequently identified. For each of the 97 respondents identified, the interview lasted between 30 to 110 minutes. Dairies were used to record the data.

Direct observations were used to understand the reasons behind the different field practices at the level of biogas plants. This provided a lived experience of the problems related to the implementation of biogas technology. An observation guide was prepared to this effect, and the data were recorded in a diary. Data collected through direct observation was triangulated with the results of the interviews. Biogas plants were identified in the following regions of Cameroon: North West (Bamenda), Central (Yaounde), West (Bafoussam, Foumbot, Mbouda, Dschang), East (Bertoua), Adamawa (Ngaoundere) and Far North (Maroua).

Table 6.2. Data sources, number of respondents and methods of data collection

Data source	No. of respondents	Method of data collection	
Expert organisations	**22**		
Ministry of Energy and Water Resources	10		
Ministry of Agriculture and Rural Development	3		
Ministry of Fisheries, Livestock and Animal Husbandry	2		
Biogas entrepreneurs and masons	2	Interviews	Purposeful sampling
Ministry of Higher Education (universities)	5		
Non-governmental organisations	4		
Key informants	**17**		
Communal mayors, administrators, traditional authorities			
Biogas users (farmers)	**51**	Interviews and direct observation	Snowball sampling
Men	33		
women	18		
Total	**92**		

The main functions that influence technological innovation systems and the guiding interview questions used in this study are shown in Table 6.3.

Table 6.3. Innovation system functions

Systems function		Guiding interview questions
F1	Entrepreneurial activities	Are there sufficient and suitable actors contributing to biogas technology diffusion? What do you know about the interventions or experiments and scale of biogas technology implementation in Cameroon
F2	Knowledge development	Are there enough and competent actors involved in knowledge development? Is knowledge development sufficiently aligned with actors' needs?
F3	Knowledge diffusion	Do you have sufficient networks or connections through which knowledge is exchanged? What motivated you to implement biogas technology?
F4	Guidance of the search	Do actors and institutions provide sufficiently clear direction for future development?
F5	Market formation	Size of market sufficient to sustain entrepreneurial experimentation and innovation? Any standards and regulations related to biogas technology?
F6	Resource mobilisation	Sufficient financial resources? Sufficient and competent actors to implement project? Sufficiently designed, constructed and well managed biogas plant (infrastructure)?
F7	Creation of legitimacy/advocacy	Do actors, formal and informal institutions sufficiently contribute to legitimacy? How much external support or resistance is present towards the technology?

To understand the causes of the slow transition to biogas energy in rural Cameroon, the collected data were cleaned, coded and the TIS framework was applied to understand the evolution and identify the structural and functional problems hindering the development of Cameroon's biogas innovation system. During the coding of the data, a triangulation of data from the document study, interviews and direct observations was performed. The triangulated data was organised according the different structural and functional elements and time periods. Expert Elicitation (EE) scores were used to assess the impact of the different functional problems on the development of the biogas innovation system. A 5-point Likert scale was used to assess the expert scores of the problem hampering the TIS functions as follows: 0.1 – 1.0 = very low, 1.1 – 2.0 = low, 2.1 – 3.0 = medium, 3.1 – 4.0 = high, 4.1 – 5.0 = very high hindering effect. The mean scores of the functional problem were calculated, visualised in a radar diagram and compared. Finally, the causes of the systemic problems were identified and organised into different categories as identified by Negro et al. (2012) and others identified by the authors.

6.5. Results and Discussion

6.5.1. Structural elements and problems

Actors and network formation

The biogas innovation system has been influenced by both national and international actors. The main national actors influencing the transition to small-scale biogas technology include the government, non-governmental organisations, renewable energy enterprises (REEs), micro-finance institutions, universities and biogas users (farmers and non-farmers). In rural areas, the main implementers of biogas technology are small-scale cattle, pig and poultry farmers. Local non-governmental organisations (NGOs) and international organisations create awareness, provide technical expertise, capacity-building and, in some cases, funding to rural dwellers and farmers for the construction of biogas plants. Renewable energy enterprises contribute to creating awareness, designing and constructing the BGPs, and providing maintenance services. In developing countries, micro-finance institutions play a significant role in providing initial funding for the construction of biogas projects (Knoema 2023). Most respondents revealed that these institutions are not yet funding rural biogas projects and lack accurate knowledge about the viability and assessment of biogas projects. The diffusion of small-scale biogas technology is continuing in Cameroon due to the training of technicians and engineers by private and public universities. There exist several government ministries coordinated by MINEE addressing development issues (setting policies, regulations, and providing incentives) of renewable energy, including biogas technology. The main international organisations that have significantly influenced the diffusion of biogas technology in Cameroon are the Netherlands Development Organization (SNV) and Heifer Project International (HPI). SNV was mainly involved in designing and implementing the NBP from 2009 to 2014. The HPI successfully implemented a biogas project in Santa Sub Division in collaboration with MINADER.

On the contrary, there are no formal networks of biogas actors in Cameroon. The government of Cameroon has been advocating for the formation of a network of actors to address issues related to the development of biogas technology. Currently, the small-scale biogas technology development network is informal and comprises international (through development aid and bilateral support) and country-based actors such as government, NGOs, biogas users, the private sector and micro-finance institutions. The alignment of the network these actors is poor, resulting in a weak or no cooperation between them. Farmer-to-farmer communication is dominant in rural areas and is also very poor. The respondents also revealed that there is low engagement of women in decision-making to transition to biogas energy. MINEE, through the DDRE, plays the role of the system builder, but inadequate coordination and action are leading to the low diffusion of biogas technology. According to the DDRE of MINEE, there is a need to strengthen the network of these biogas actors to improve the diffusion of the technology.

6.5.2. Institutional aspects

Enabling the transition to small-scale biogas technology is the task of several government ministries coordinated by MINEE. The MINEE is the main ministry charged with establishing and implementing government policies related to the production, transportation, and supply of water resources and energy, as well as the promotion of renewable energy. In addition to MINEE, the consortium of government ministries/institutions charged with the development of Renewable Energy include the Rural Electrification Agency (AER), Ministry of Forests and Wildlife (MINFOF), National Forestry Development Agency (ANAFOR), Ministry of Environment, Nature Conservation and Sustainable Development (MINEPED), Energy Management Committee, and the World Energy Council (WEC) Cameroon Committee. The NBP was implemented by MINEE, Ministry of Livestock, Fisheries and

Animal Industries (MINEPIA), Ministry of Finance and Budget (MINFIB), Ministry of Environment and Nature Protection (MINEP), Ministry of Agriculture and Rural Development (MINADER), former Ministry of Planning, Development Planning and Regional Development (MINPLADAT), Ministry of Women's Empowerment and the Family (MINPROFF). The MINEE has personnel at the central, regional and communal offices. Subsidies up to 30% of the initial construction cost were reimbursed to farmers during the NBP (MINEE 2010). Since the introduction of government's initiatives in 1979 to promote the biogas technology, the construction of biogas plants has been co-financed by several development agencies to offset the initial investment cost. Apart from subsidies, the government and its partners have trained biogas technicians and farmers on the construction, operation, and maintenance of biogas plants. The sharing of tasks between different government ministries renders institutional response slow. The absence of a regulatory framework and standards exacerbates the institutional gap in enabling the sustainable transition to biogas technology in rural areas of Cameroon. A summary of the problems hindering the development and diffusion of biogas technology are shown in Table 6.4.

5.5.2. Functional elements and problems

This section seeks to understand the state of development of each function while identifying the problems hindering the development of the biogas innovation system in Cameroon. The identified problems constitute the main blockages leading to the slow transition to biogas energy in rural areas of Cameroon.

5.5.3. First phase: Initiation and early functioning of biogas innovation system (1979 - 1983)

The results of the document analysis and interviews show that the promotion and diffusion of small-scale biogas technology began around 1979. This marked the beginning of the development of the small-scale biogas innovation system. The National Center for Studies and Agricultural Mechanization Experimentation (CENEEMA) coordinated biogas activities at this time. It was aimed at providing biogas and organic fertiliser from organic waste to rural areas. Entrepreneurial activities began with the construction of biogas plants by German experts (Steedman 1979). From 1979 to 1983, the CENEEMA built 29 biogas plants across the country. The North West and Littoral regions had 17 biogas installations. The major problem encountered during this phase is that the biogas plants that were constructed in individual farms and hospitals immediately stopped working due to competition with grid electricity (GVC 2012) and firewood. These biogas plants were intended to be used for experimentation, adapting to local conditions, or demonstration. Hence, knowledge development and knowledge diffusion.

Three biogas plant models, with capacities varying from $1m^3$ to $10m^3$, were tested during this phase: the Chinese, Indian and German (Darmstadt) models. None of the three models was adapted to the local (rural and climatic) conditions of Cameroon. The Chinese model had many problems, such as gas leakage and pressure not being constant. The Indian model had to be abandoned due to the difficulties in digestate discharge. The German model (Darmstadt) was expensive, and the mechanical mixer occasionally choked, especially after a prolonged period of non-use. To address these difficulties, CENEEMA designed a new model (CM2013) combining the Indian and Darmstadt models. Two biogas plants were constructed at Bandjoun and Bali hospitals, among others. After four years of operation, a review showed that 50% were in good operating condition, 30% stopped operating because of the lack of regular maintenance, and 20% stopped operating for other reasons.

During this phase, the National Advanced School of Public Works, Yaoundé (NASPW) was the only higher institution developing and testing new prototypes of biogas plants. Students were sought and sent to the United States of America (USA) to gain more knowledge on biogas technology. Resources were also mobilized to fund biogas research in Cameroon. The failure to adapt biogas technology during this phase led to the intensification of biogas knowledge development in the following phases.

5.5.4. Second phase: Functional slum (1984 – 2008)

Activities to promote biogas technology from 1984 to 2008 slowed down, compared to the previous phase, due to the challenges faced by CENEEMA. During this period of functional 'slum', isolated biogas promotion initiatives were implemented by NGOs. Entrepreneurial activities continued with the construction of biogas plants. These NGOs also participated in knowledge diffusion by creating awareness about biogas technology. However, due to lack of funding, their activities were successful but had very little impact on the national scale. Most of the initiatives during this period were short-lived because the little successes achieved did not create any significant policy shift to promote biogas technology (GVC 2012). In the same period, knowledge development continued with CENEEMA on researching the best biogas plant design for the Cameroonian context. The Renewable Energy Laboratory and the ENSAI Ngaoundere also became active in developing knowledge on biogas technology. These institutions received insignificant research and development (R&D) funding. Consequently, knowledge development slowed down considerably. On a positive note, guidance of the search took steam during this period. Several government ministries considered promoting biogas technology as a means to provide cleaner alternative to firewood and other polluting fuels used for cooking in households. During this period, the government of Cameroon ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 (United Nations Treaty Collection 1994) and the Kyoto protocol (United Nations Treaty Collection 2002). The Kyoto protocol and the influence of the United Nations Framework Convention on Climate Change (UNFCCC) have encouraged the government and partners to look at biogas systems as a way to replace firewood, kerosene and LPG as cooking fuels.

5.5.5. Third phase: Functional revival and acceleration (2009 – 2014)

This represents the period of the design and implementation of the National Biogas Programe. The NBP was aimed at creating a local biogas market. This programme also aimed to enable tangible and quantifiable improvements in the quality of life in rural households and general rural population of Cameroon; through the propagation and sustained use of domestic biogas plants taking full consideration of the multiple benefits associated with it (GVC 2012). The 5-year (2009-2014) NBP was supported by SNV (Ghimire 2013). Six functions of the biogas innovation were addressed though not equally during this phase of development of the biogas innovation system. Entrepreneurial activities were more evident with the construction of biogas plants. With the focus on the fixed dome masonry biogas plants, several local enterprises supplied the construction materials. These materials include masonry (sand, gravel), plumbing, cookers, gas bags and plastic biogas plants. No companies specialised on biogas plant construction existed. However, the construction of biogas plants was facilitated by two local NGOs, Action for a Sustainable, Equitable and Integrated Development (ADEID) and African Centre for Renewable Energy and Sustainable Technologies (ACREST). During the NBP, with the support from SNV, 198 biogas plants were constructed in Cameroon (Ghimire 2013). This number was far below the 1000 biogas plants planned to be constructed during the programme. During this phase, knowledge development was also observed in the form of feasibility studies of biogas technology, conducted by SNV (international actor) and local actors. The technical, economic and social feasibility studies were conducted during this period. Knowledge diffusion was a major activity during the NBP. The SNV consultants participated in creating awareness, providing technical advice and building beneficiaries' capacity for the construction of biogas plants. The NBP created very high expectations at the national and farm levels about the relevance of biogas in the national energy mix. Guidance of search became more relevant as the government included biogas technology as one of the sources of energy to attain emergence by 2035 (MINPLADAT 2009). With the goal of the NBP to create a local biogas market, subsidies were provided to farmers with a source of feedstock and water to build their biogas plants. Subsidies reduced the burden of the high investment cost on the farmers. A local resource base was essential to enable the sustainability of the technology. Human capacity in the form of masons or technicians was developed to provide technical advice to biogas users and potential adopters. Biogas technicians were trained during the NBP and in various national and international higher institutions. During the NBP implementation period, Heifer International in collaboration with the Ministry of Agriculture and Rural Development (MINADER) implemented a parallel biogas project in Santa Subdivision in the North West Region of Cameroon (GVC 2012). By the end of 2014, a total of 300 domestic biogas plants were constructed in Cameroon (IRENA 2017). This was partially considered as a failure of the NBP.

5.5.6. Fourth phase: Deliberate functioning (2015 – 2022)

At the end of the NBP and the MINADER/Heifer International project, the functional status of biogas innovation system improved but the achievements were far below target. The deliberate functioning phase witnessed the recession in government's involvement in the development of the technology. Entrepreneurial activities were carried out by the private sector, including NGOs, private companies and individuals. After the NBP, only one local enterprise known as Green Power Biotechnology (a startup company) was created and is currently designing, constructing and providing technical advice to farmers and biogas users. Local NGOs are continuing to provide biogas services to farmers. For example, the Royal Renewable Energy Cameroon (RRECAM) and others are offering biogas services to farmers. Farmers revealed during the interviews that entrepreneurial activities are scarce and costly in rural areas since most of the enterprises are based in urban areas. These two entrepreneurs have created an informal network of local biogas plant technicians in addition to the technicians trained during the National Biogas Program (2010 – 2014) by SNV and Heifer International. They also collaborate with municipal councils to build biogas plants to treat communal waste. An international actor such as the United Nations Environment Program, through its Ecosystem-Based Adaptation for Food Security Assembly (EBAFOSA) platform, has funded small-scale community biogas plants (to inspire shared production and use of biogas). Community biogas plants enable joint management and sharing of benefits of biogas plants. According to the users, community biogas plants reduce the financial burden on the farmers and promotes social adaptation of the technology. To optimise the benefits of the biogas plants, some biogas plant owners engaged in the productive use of biogas. These include NGOs, religious institutions (monasteries and churches) and commercial pig farms. Despite the availability of biogas service providers, the quality of the biogas plants constructed differs from one mason or technician to another. This is evident by the failure of some of the biogas plants after construction or a short period of use. According to the farmers, most of the constructed biogas plants failed due to poor design and construction.

Most literature revealed that biogas technology is well understood in Cameroon (Ndongsok et al. 2018; Darnhofer 2015). Knowledge development is considered the most fulfilled function of the biogas innovation system in Cameroon. Knowledge diffusion was still lacking during this period. Widespread lack of knowledge about biogas technology still exists, especially in rural areas of Cameroon. The government diffused knowledge on biogas technology through its decentralised offices. The government personnel in these offices served as extension agents. The main problem highlighted by these offices is the lack of staff and the resources to meet the farmers and advise them. According to some of the officers, the extension services are poorly coordinated and, therefore, not effective. This has resulted in a lack of adequate knowledge of the operation and maintenance of small-scale biogas plants among rural dwellers and farmers. The NGOs are currently the main actors in diffusing biogas knowledge in rural areas of Cameroon. For example, "Green Girls" has since 2015 trained over 800 women in 23 communities on biogas production from toilet waste and advocated for women's and girls' inclusion in the renewable energy sector (ADB & Women 2021). RRECAM, on the other hand, organises paid training sessions on biogas technology across the country. Private companies also advertise the technology by word of mouth. In addition, these private firms and NGOs are currently using social media platforms such as YouTube, Instagram, and Facebook to create awareness on biogas technology. Unfortunately, most farmers in rural areas have limited access to internet and these platforms. During the experimentation period, biogas plants were constructed in hospitals. Unfortunately, most of these biogas plants failed, leading to the abandonment and lack of interest among the rural population.

In relation to guidance of the search, the government was particularly interested in seeking the promotion of circular economy, development of "green" jobs and expansion of clean household energy. The Cameroon's Sustainable Energy for All Action Agenda seeks by 2030 to enable universal access to clean and modern energy for cooking by 99% in rural areas

(Rubinstein et al. 2021). This aligns with the 2020 - 2030 National Development Strategy and Cameroon’s 2035 vision for an emerging country. However, diverging perceptions and visions about biogas technology are impeding several functions of biogas innovation. Some experts, during the analysis of Cameroon’s clean energy transition, perceived biogas technology as not having a great potential in Cameroon (Ndongsok et al. 2018).

The biogas market is still extremely immature. The number of constructed small-scale BGPs is not known in Cameroon. So far, over 500 small-scale BGPs have been reported (less than 1% of the technical potential). In 2018, the technical potential of household biogas plants in Cameroon was estimated to range from 284,000 to 724,000 biogas plants. The ‘technical potential’ is referred to as the number of households that can meet the two basic requirements – sufficient availability of dung and water – to operate a biogas plant (SNV 2018). The share of biogas energy in the energy mix in rural areas of Cameroon is still very low due to high competition with firewood. The demand for the technology is defined mostly by the knowledge about the technology, and the capital investment cost. Since the end of the NBP in 2014, the government has prioritized the promotion of liquefied petroleum gas (LPG) (Bruce et al. 2018) and biogas from municipal solid waste (MSW), taunting the development of the domestic biogas market. Generally, the biogas market is still immature and does not have an institutional arrangement to allow the alignment and participation of the market actors. The value of digestate, a by-product of anaerobic digestion, is not well known in Cameroon, leading to low demand and, consequently, its underutilisation.

Resource mobilisation continues to be one of the major hurdles of the biogas transition in Cameroon. In rural areas, the farmers declared their inability to pay for maintenance services and the new biogas plants. According to them, their farming activities are small-scale, enough to feed their households, with savings not enough to pay for the biogas plants. In addition, there is still inadequate access to skilled biogas technicians. Therefore, the number of technicians does not meet the demand of farmers. The government is highly overdependent on donor and external funding for the development of the local biogas market. National funding for biogas technology is still insignificant and mostly non-existent. No biogas-specific budgets were available at the national level.

The legitimacy function of the biogas innovation system is less developed. The government is still not sufficiently engaged to define policies to promote biogas technology in Cameroon. Informal groups engaged in the advocacy of biogas technology are mainly non-governmental organisations. The quest to conform with global demand to transition to renewable remains a major motivator for the government to create legitimacy. International organisations such as the French Agency for Development (AFD) and related French international development organisations are advocating for the promotion of biogas technology and other renewable energies in Cameroon. The Cameroon Sustainable Development Goals (SDGs) action plan advocates for the creation of legitimacy for biogas technology for clean cooking. The major laws and initiatives implemented in Cameroon since 1979 are shown in Figure 6.2. The main feature on Figure 6.2 is the lack of regulation or policies to promote the diffusion of biogas technology in Cameroon.

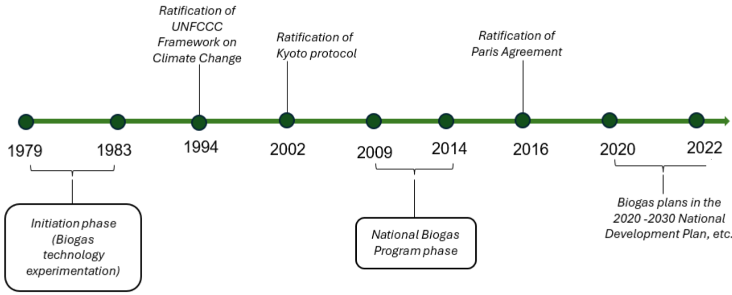


Figure 6.2. Initiatives and engagements related to the development of the biogas technology in Cameroon

6.5.3. Impact of TIS functions hindering the biogas energy transition

Expert evaluation was used to understand the current performance of the functions of the biogas innovation system. The mean scores (in brackets) of the functions of each of the TIS functions were estimated. A high score implies a higher s effect and vice versa. A comparison of the scores of the functional problems shows the highest score for F3: knowledge diffusion (4.7). This shows that lack of awareness about biogas technology is contributing the most to the slow development of the biogas innovation system and, consequently, the slow transition to biogas technology in rural areas of Cameroon. The lowest score was found for F2: Knowledge development (1.0). According to the experts and triangulation of problems collected from document study, biogas technology is well understood in Cameroon, but other factors are hindering its development. The other functions from the strongest to the weakest problem strength include F6: resource mobilisation (4.0), F7: creation of legitimacy/advocacy (3.7), F5: market

Table 6.4. Summary of structural and functional problems hindering the development of biogas technology in Cameroon

Structural element	Problems
Actors	Inadequate number of entrepreneurs leading to near monopoly in service delivery
	Biogas users lack adequate knowledge of the technology
	Inadequately skilled technicians
	Acute lack of awareness of biogas technology in rural areas
	Inadequate knowledge capacity of extension agents (government staff)
	Low engagement of women in biogas decision-making
Networks	
	Lack of formal networks of the implementers of biogas projects
	Lack of rural or farm organisations addressing biogas technology issues
	Partial dependence on imported biogas plants and appliances
Institution	
	Lack of subsidies and credits
	Lack of framework for financial institutions to fund biogas projects

	Lack of legal framework and biogas technology standards
	Lack of national biogas and/or bioenergy policy
	Inadequate involvement of biogas stakeholders in decision-making
	Lack of common vision for biogas technology development
	Insufficient monitoring and reporting on biogas projects
	Inadequate funding for R&D to promote biogas technology
	Overdependence on foreign financial aid for biogas technology development
Technology	
	High cost of biogas plants
	Widespread technical failures on biogas plants
	Poor performance of biogas plants
	Very high competition with LPG and solar energy projects

formation (3.5), F1: entrepreneurial activities (3.0) and F4: guidance of search (1.9).

Figure 6.3. Impact of functional problems on the current biogas innovation system

6.5.4. Systemic problems causing the slow biogas energy transition

The core systemic problems causing the slow transition to small-scale biogas technology in Cameroon include weak institutional setting, lack of legitimacy of biogas technology, weak biogas actor-network formation, farmers inability to pay for biogas plants, and lack of capabilities to sustain biogas energy supply.

i) Weak institutional setting

The biogas actors revealed that the existing institutional setting is not sufficient for the significant development and diffusion of biogas technology in Cameroon. At the government level, hard institutional problems such as the lack of policy, subsidies/financing mechanisms, standards and regulations, knowledge diffusion (extension services) hinder biogas market formation. In rural areas, these hard institutional problems render resource mobilisation difficult for the farmers, leading to low adoption of biogas technology. Trained biogas technicians are few in the country leading to the high cost of biogas services in rural areas. The soft institutional problems identified in this study include overdependence of rural and peri-urban households on fuelwood and charcoal for cooking energy needs. Firewood is seen as a norm in most of the households (Atyi et al. 2016).

ii) Lack of legitimacy of biogas technology

There is acute lack of awareness about biogas technology especially among smallholder farmers in rural areas of Cameroon. There is divided perception of biogas technology among the actors. Farmers revealed some of the non-biogas users still perceive biogas from animal faecal material as dirty and contagious. Some experts suggest that biogas technology cannot be considered for a specific legal framework because it does not have a significant potential and sustainability problems (Ndongsok et al. 2018). This contributes to hindering biogas market development. While the Cameroon's biogas innovation is influenced by the international energy system, there is need to lobby for global funding for national biogas projects. In addition, local and international development and research institutions could collaborate to develop low-cost biogas plant models for farmers, facilitate access to funds related to clean development mechanism and strengthen local knowledge capacity in financial management. These actors could also lobby to increase biogas funding in national budgets.

iii) Weak biogas actor-network formation

There is very weak interaction among biogas actors in Cameroon. At the government level, there is weak coordination of the different institutions tasked to influence the biogas sector. There are very few opportunities for the rural farmers to access funding for their biogas projects. Due to the absence of regulatory and financial mechanisms, micro-finance institutions perceive biogas technology as risky investment. Consequently, there are no identified financial institutions awarding loans to farmers to fund biogas projects. At the farm level no formal farmers' organisations exist to promote biogas technology. However, informal networks of farmers exist. Farmer-to-farmer communication and collaboration exist in rural areas, but they are ineffective and inadequate. In one case, farmers collectively provided organic waste to a community biogas plant and in return, each receives biogas in plastic bags of one cubic metre for cooking. Other existing farmer associations such as common initiative groups (CIGs) and cooperatives could integrate biogas technology in their production activities. Farmers also revealed that they don't have access to government extension services related to biogas technology.

iv) Farmers inability to pay for biogas plants

Most rural farmers are unable to pay the capital investment cost of biogas plants due to low household income (poverty). According to some farmers, the revenue from the subsistence agriculture and livestock they practice cannot fund the construction of biogas plants. The cost of the masonry fixed dome biogas plant is higher in Cameroon than in other parts of sub-Saharan Africa as shown in Table 6.5. Most of the rural farmers revealed that the income from their livestock and farming activities cannot pay upfront for the biogas plants. During the NBP, subsidies enabled more farmers to adopt biogas technology. According to the farmers, the biogas technician's labour cost accounts to an average 25% of the total investment cost of the biogas plant. The high labour cost is caused by the lack of biogas service providers. There is very little competition in biogas service delivery in the country. It was observed that the average tropical livestock units (TLU) per rural or farming household is 2.6 cattle. This indicates that some farmers still cannot access biogas feedstock to produce sufficient biogas quantity to replace firewood and kerosene. A common strategy to overcome this deficit would be to facilitate access to livestock to the farmers to increase biogas feedstock production and empower rural economy to acquire biogas plants. In relation to the materials used for the construction of the biogas plants, the farmers revealed that the masonry biogas plants were more expensive than the plastic ones. The farmers preferred low-cost portable plastic biogas plants due to their low cost. Nevertheless, the lifespan of these biogas plants is shorter (between 5 to 10 years). Asked, the farmers revealed that the savings from portable plastic biogas plants within the 5 to 10-year period could, in the long run, lead to the acquisition of more durable masonry biogas plants.

Due to the financial constraints faced by the farmers, there is a need for regulation (in the form of a legal framework) of the biogas market. In addition, farmers need subsidies or loans to acquire biogas plants.

Table 6.5. Variation of the total investment cost of $8m^3$ fixed dome biogas plant in selected sub-Saharan African countries

Country	Cost (US$)	Year	Reference
Cameroon	1800	2024	Ketuama and Roubík (2024)
Senegal	1244	2023	Ndiaye et al. (2023)
Rwanda	749	2023	hope-mag (2023)
Nigeria	1365	2020	Aikhuele (2020)

v) Lack of capabilities to sustain biogas energy production and consumption

The lack of skilled technicians has led to the delivery of poorly designed and low-quality biogas plants. The farmers are poorly trained by the biogas technicians after acquiring the biogas plants leading to the failure in some cases. The lack of farmers' capacity to manage the biogas plants led to several operational problems. Some of the observed problems include poor loading of biogas, low gas production, malfunctioning of biogas cooker, poor digestate handling and use, failure of biogas plants (non-functional), and poor maintenance. Another factor hindering the operation of biogas plants is poor access to water. About 32% of the farmers did not have an adequate amount of water to operate their biogas plants. This contributed to the underutilisation of their biogas plants and the complete failure of one of the biogas plants. Figure 6.4 shows the prevalence of the observed technical problems causing the failure of some of the biogas plants.

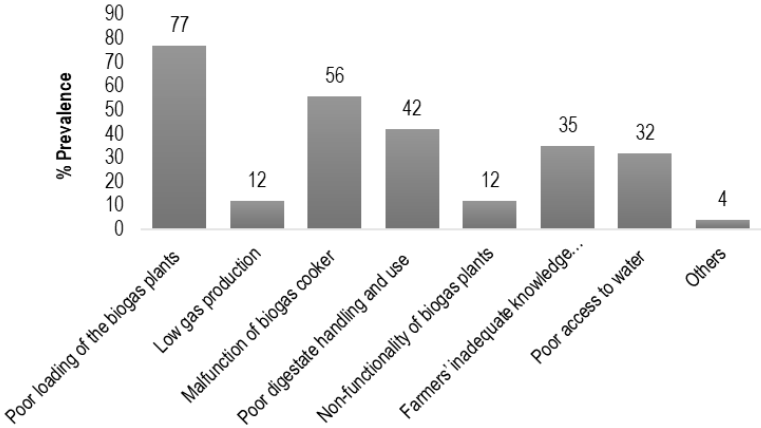


Figure 6.4. Prevalence of some technical problems on small-scale biogas plants in Cameroon

6.6. Policy implications

This study reveals that the Cameroon's biogas innovation system is very weak and requires improvement in the institutional setting, legitimacy, biogas actor-network, farmers' capacity to pay for biogas plants and capabilities to sustain the technology. Future biogas innovation system building requires institutional support in terms of the policy, legal framework, standards and subsidies. Government efforts to promote the biogas technology will have to build a network of biogas actors. The involvement and perceptions of women and youths should be taken into consideration, given that they are more active in cooking than men in rural areas. An interministerial task force is needed to focus on the promotion of biogas technology. This implies that a stronger coordination is required from MINEE. This study showed that most of the current biogas users learned about biogas technology from local NGOs, biogas technicians and personnel of the biogas enterprises. Community outreach programs (e.g. demonstrations, farmer field schools), educational campaigns, and extension services can contribute to increasing awareness of biogas technology. To enable the expansion of the biogas market, financing mechanisms are needed to source and reduce the financial burden on farmers or potential biogas users. Finally, there is a need to build local technical capacity to sustain the technology. This will require more biogas technicians and further training of farmers on the efficient management of biogas technology to optimise the benefits. In addition, the related decentralised government services should provide a monitoring mechanism to ensure the effectiveness of the biogas projects.

6.7. Conclusion

The purpose of this study is to understand the causes of the slow transition to biogas energy in rural areas of Cameroon. The technological innovation systems approach was used to identify the structural and dynamic elements hindering the development of small-scale biogas technology. Structural elements are emerging but falling short of expectations. International and national actors are contributing to the enabling biogas energy transition in rural areas of Cameroon. However, there is a lack of continuity in their activities. The network of actors is informal, and its alignment is weak, resulting in inadequate cooperation between the different biogas actors. Farmer-to-farmer communication and collaboration exist in rural areas, but they are ineffective and inadequate. Several government ministries have plans to contribute to the development of biogas technology in Cameroon, but little action has been observed. The causes of institutional failure include poor coordination of the public and private sector actors. Collaboration between these institutions is minimal due to lack of a common vision. There is no biogas policy, regulations, standards, and subsidies. The evolution of the functional or dynamic elements showed a significant number of problems at each stage. Knowledge diffusion is the major block to biogas energy transition. There is acute lack of awareness about the technology in rural areas. Knowledge development is well developed but the major challenge remains to build the capacity of the different biogas actors. To enable biogas energy transition in rural areas of Cameroon, there is a need to strengthen the biogas innovation system by finding solutions to innovation problems or gaps. Major issues to be addressed to improve biogas energy transition include improving the institutional setting, legitimacy, building farmers'/actors' actor-networks, creating awareness at the local or farm level, mobilising local and international financial resources for small-scale biogas projects.

This study provides knowledge on the biogas innovation process including the problems and policy recommendations. While the TIS analysis provided the whole system analysis, further specific research will be relevant on *i)* disruptive biogas technological innovations, *ii)* biogas actor mapping, *iii)* knowledge flows within the innovation system, *iv)* shaping the evolving political changes to promote biogas technology, and *v)* financial flows to develop the biogas innovation system. This will shed more light on the local capabilities, and opportunities needed to strengthen the biogas innovation system.

References

ADB, UN Women. 2021. Emplois verts pour les femmes en Afrique. UN Women. Available from https://www.afdb.org/sites/default/files/documents/publications/un_women_green_jobs_report_fr_0.pdf (accessed on 3 June 2023).

Aikhuele J, Eniola V, Aikhuele A, Fasipe O, Awuapila N. 2020. The Implementation of Biogas Production from Municipal Solid Waste in Nigeria. Journal of Energy Technologies and Policy, 10, 1. ISSN 2225-0573. doi: 10.7176/JETP/10-1-06.

Atyi ER, Ngouhouo P, Mvondo A, Ngoungoure M, Sufo K. 2016. Economic and Social Importance of Fuelwood in Cameroon. International Forestry Review, 18(2), 1–14. doi: 10.1505/146554816819683735.

Aziz EM. 2020. Key problems and proposed solutions to Cameroon’s energy sector. Nkafu Policy Institute. Available from https://nkafu.org/key-problems-and-proposed-solutions-to-cameroons-energy-sector/ (accessed on 23 September 2023).

Bergek A, Jacobsson S, Carlsson B, Lindmark S, Rickne A. 2008. Analysing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy 37, 407–429.

Bijker, W.E. Hughes, T.P., Pinch, T.J. (eds). (1987). The Social Construction of Technological Systems: new directions in the sociology and history of technology, MIT Press, Cambridge, Massachusetts, USA.

Bluemling B, Mol APJ, Tu Q. 2013. The social organization of agricultural biogas production and use. Energy Policy 63, 10-17. doi: 10.1016/j.enpol.2013.08.035.

Blum NU, Bening CR, Schmid TS. 2015. An analysis of remote electric mini-grids in Laos using the Technological Innovation Systems approach. Technological Forecasting & Social Change 95, pp. 218–233. doi: 10.1016/j.techfore.2015.02.002.

Borges CP, Silberg TR, Uriona-Maldonado M, Vaz CR. 2023. Scaling actors' perspectives about innovation system functions: Diffusion of biogas in Brazil. Technological Forecasting and Social Change, 190, 122359. doi: 10.1016/j.techfore.2023.122359.

Bruce N, Anderson de Cuevas R, Cooper J, Enonchong B, Ronzi S, Puzzolo E, Mbatchou B, Pope D. 2018. The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation. Energy for Sustainable Development, 103-110. doi: 10.1016/j.esd.2018.05.010.

Darnhofer I. 2015. Socio-technical transitions in farming: Key concepts. In L. Sutherland, I. Darnhofer, G. A. Wilson, & L. Zagata (Eds.), Transition pathways towards sustainability in agriculture: Case studies from Europe (1st ed., pp. 17–31). CABI. doi : 10.1079/9781780642192.0017

Diouf B, Miezan E. 2019. The Biogas Initiative in Developing Countries, from Technical Potential to Failure: The Case Study of Senegal. Renewable and Sustainable Energy Reviews, 101, 248–254. doi: 10.1016/j.rser.2018.11.011.

Edsand H. 2019. Technological innovation system and the wider context: A framework for developing countries. Technology in Society, 58, 101150. doi: 10.1016/j.techsoc.2019.101150.

Fulford D. 2015. Small-scale, rural biogas programmes, Rugby, UK: Practical Action Publishing. doi: 10.3362/9781780448497.

Ghimire PC. 2013. SNV supported domestic biogas programmes in Asia and Africa. Renew Energy 49:90–94. doi: 10.1016/j.renene.2012.01.058.

GVC (Global Village Cameroon). 2012. Etat des lieux du cadre règlementaire du secteur des énergies renouvelables au Cameroun. Rapport d'analyse.

Hekkert MP, Suurs RAA, Negro S, Kuhlmann S, Smits RE. 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Chang. 74, 413–432. doi: 10.1016/j.techfore.2006.03.002.

Hewitt J, Holden M, Robinson BL, Jewitt S, Clifford MJ. 2022. Not quite cooking on gas: Understanding biogas plant failure and abandonment in Northen Tanzania. Renewable Energy and Sustainable Energy Reviews, 165, 112600. doi: 10.1016/j.rser.2022.112600.

hope-mag. 2023. Biogas dissemination. Available from https://hope-mag.com/biogas-dissemination/ (accessed 12 September 2023).

IRENA. 2017. Biogas for domestic cooking. Technology brief, International Renewable Energy Agency, Abu Dhabi.

Jacobsson S. 2008. The emergence and troubled growth of a "biopower" innovation system in Sweden. Energy Policy 36, 1491–1508. doi: 10.1016/j.enpol.2007.12.013.

Kabeyi MJB, Oludolapo AO. 2022. Biogas Production and Applications in the Sustainable Energy Transition. Journal of Energy. doi: 10.1155/2022/8750221.

Kalina M, Ogwang JÒ, Tilley E. 2022. From potential to practice: Rethinking Africa's biogas revolution. Humanit. soc. sci. 9(1):374. doi:10.1057/s41599-022-01396-x.

Kebede KY, Mitsufuji T. 2016. Technological innovation system building for diffusion of renewable energy technology: A case of solar PV systems in Ethiopia. Technological Forecasting and Social Change, 114, 242-253. doi: 10.1016/j.techfore.2016.08.018.

Ketuama CT, Roubík H. 2024. Economic viability and factors affecting farmers' willingness to pay for adopting small-scale biogas plants in rural areas of Cameroon (unpublished).

Ketuama CT, Mazancova J, Roubík H. 2022. Impact of market constraints on the development of small-scale biogas technology in Sub-Saharan Africa: a systematic review, Environ. Sci. Pollut. Res. 29 65978–65992. doi : 10.1007/s11356-022-22262-y.

Kidmo DK, Deli K, Bogno B. 2021. Status of renewable energy in Cameroon. Renewable Energy and Environmental Sustainability, 6, 2. Doi: 10.1051/rees/2021001.

Knoema. 2023. Cameroon - Poverty headcount ratio at rural poverty line as a share of rural population. Available from https://knoema.com/atlas/Cameroon/Rural-poverty-rate#:~:text=Cameroon%20rural%20poverty%20rate%20was,the%20national%20rural%20poverty%20line (accessed on 23 September 2023).

Koirala BP, van Oost E, van der Windt H. 2018. Community energy storage: A responsible innovation towards a sustainable energy system? Applied Energy, 231. pp. 570-585. doi: 10.1016/j.apenergy.2018.09.163.

Lundvall BA, Johnson B, Andersen ES, Dalum B. 2002. National systems of production, innovation and competence building. Research Policy, 31(2), 213-231. doi: 10.1016/S0048-7333(01)00137-8.

Markard J, Hekkert M, Jacobsson S. 2015. The technological innovation systems framework: Response to six criticisms. Environmental Innovation and Societal Transitions, 16, pp. 76-86. doi: 10.1016/j.eist.2015.07.006.

Markard J, Truffer B. 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy 37, 4, 596-615. doi: 10.1016/j.respol.2008.01.004.

MINEE (Ministry of Water Resources and Energy). 2010. National Biogas Programme. Blue Flame for Brighter Future for Cameroon.

MINPLADAT. 2009. Cameroon Vision 2035.

Muh E, Amara S, Tabet F. 2018. Sustainable energy policies in Cameroon: A holistic overview. Renew. Sust. Energ. Rev. 82:3420–3429. doi:10.1016/j.rser.2017.10.049.

Ndiaye M, Sene M, Ndiaye G, Sadio EL. 2023. Construction Technology of Biodigesters in Senegal. Energy and Power Engineering, 15, 329-339. doi: 10.4236/epe.2023.1510018.

Ndongsok D, Mandeng T, Azemtsa H, Tankeu C, Ruppel CO. 2018. The state of biofuels development in Cameroon. Selected policy recommendations for sustainable biofuels production.

Negro SO, Alkemade F, Hekkert MP. 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renewable and Sustainable

Energy Reviews, 16, 3836-3846. doi: 10.1016/j.rser.2012.03.043.

Negro SO, Hekkert MP, Smits RE. 2007. Explaining the failure of the Dutch innovation system for biomass digestion—A functional analysis. Energy Policy 35, 925–938. doi: https://doi.org/10.1016/j.enpol.2006.01.027.

Nelson RR, Winter S. 1982. An evolutionary theory of economic change. Cambridge : Harvard University Press. Available from https://inctpped.ie.ufrj.br/spiderweb/pdf_2/Dosi_1_An_evolutionary-theory-of_economic_change..pdf (accessed 12 March 2023).

Nightingale A. 2009. A guide to systematic literature reviews. Surgery (Oxford), 27, 9, pp. 381-384. doi: 10.1016/j.mpsur.2009.07.005.

Obaideen K, Abdelkareem MA, Wiberforce T, Elsaid K, Sayed ET, Maghrabie HM, Olabi AG. 2022. Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines. J. Taiwan Inst. Chem. Eng., 131, 104207. doi: 10.1016/j.jtice.2022.104207.

Pinch TJ, Bijker WE. 1984. The social construction of facts and artefacts: or how the sociology of science and sociology of technology might benefit each other. Social studies of science (Sage, London, Beverly Hills and New Delhi), 14, 399 – 441.

Qudrat-Ullah H. 2024. Improving Rural Electrification Access in Cameroon: A Qualitative Study. In: Exploring the Dynamics of Renewable Energy and Sustainable Development in Africa. Advances in African Economic, Social and Political Development. Springer, Cham. doi: 10.1007/978-3-031-48528-2_2.

Rubinstein F, Betang E, Mbatchou B, Pope D, Puzzolo E. 2021. Transitioning to Modern Energy Cooking Services in Cameroon A policy review of the energy sector. Department of Public Health, Policy and Systems University of Liverpool.

SNV. 2018. Technical potential for household biodigesters in Africa. Technical brief.

Steedman C. 1979. Cameroon Renewable Energy: Project Possibilities. A report to the U.S. Agency for International Development identifying actions required to develop an assessment of Cameroon's energy needs, Ann Abor, Michigan. Contract No. Afr-C1542. Project No. 698-0135. Available from https://pdf.usaid.gov/pdf_docs/PNAAH100.pdf. (accessed 12 December 2023).

Tigabu AD, Berkhout F, Van Beukering P. 2015a. Technology innovation systems and technology diffusion: Adoption of bio-digestion in an emerging innovation system in Rwanda. Technological Forecasting and Social Change, 90, 318-330. doi: 10.1016/j.techfore.2013.10.011.

Tigabu AD, Berkhout F, Van Beukering P. 2015b. The diffusion of a renewable energy technology and innovation system functioning: Comparing bio-digestion in Kenya and Rwanda. Technological Forecasting and Social Change, 90, 331-345. doi: 10.1016/j.techfore.2013.09.019.

UNFCCC. 2021. Cameroon Nationally determined contribution, Updated. Available from https://unfccc.int/sites/default/files/NDC/2022-06/CDN%20r%C3%A9vis%C3%A9e%20CMR%20finale%20sept%202021.pdf (accessed on 12 December 2023).

United Nations Treaty Collection. 1994. United Nations Framework Convention on Climate Change. Available from https://treaties.un.org/doc/Publication/MTDSG/Volume%20II/Chapter%20XXVII/XXVII-7.en.pdf (accessed 6 December 2023).

United Nations Treaty Collection. 2002. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Available from https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-a&chapter=27&clang=_en (Accessed on 6 December 2023).

Van der Laak WWM, Raven RPJM, Verbong GPJ. 2007. Strategic niche management for biofuels: analysing past experiments for developing new biofuel policies. Energy Policy, 35:3213–25. doi: 10.1016/j.enpol.2006.11.009.

Wandera FH. 2020. The innovation system for diffusion of small wind in Kenya: Strong, weak or absent? A technological innovation system analysis, African Journal of Science, Technology, Innovation and Development. doi: 10.1080/20421338.2020.1771979.

Wieczorek AJ, Hekkert MP. 2012. Systemic instruments for systemic innovation problems: A framework for policymakers and innovation scholars. Science and Public Policy, 39, 1, p.74–87. doi: 10.1093/scipol/scr008.

WIPO. 2023. Global Innovation Index 2022. Cameroon. Available online on:

https://www.wipo.int/edocs/pubdocs/en/wipo_pub_2000_2022/cm.pdf (accessed on 12 May 2023).

World Bank. 2022. Rural population (% of total population) – Cameroon. Available from https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=CM (accessed on 12 July 2023).

Yamaguchi K. 1991. Event History Analysis. Applied Social Research Methods. Sage. ISBN: 080393324X, 9780803933248. 182p.

Yin RK. 2018. Case Study Research and Applications: Design and Methods (6th ed.). Thousand Oaks, California: Sage.

General conclusion

This thesis provides an in-depth analysis of the viability and pathways of sustaining small-scale biogas technology in rural areas of Cameroon. Firstly, a systematic review of the constraints to the development of small-scale biogas technology in sub-Saharan Africa was conducted. The findings revealed that biogas technology continues to face mainly economic but also political, social, technological, environmental and legal constraints. These constraints continue to contribute to the slow adoption and diffusion of the technology in the region of which Cameroon is part.

Secondly, the economic viability of the small-scale biogas plants was assessed to determine whether they are financially viable. The results revealed that the higher the size of the biogas plants, the more viable they are. The biogas plant size meeting most of the household energy needs, especially for cooking was $8m^3$. The optimal viability of this biogas plant and others could be achieved by selling digestate or increasing its use for the fertilization of crops.

On the factors influencing rural farmers' willingness to pay for small-scale biogas plants, farmers prefer biogas technology over traditional fuelwood, charcoal and kerosene but based on the average amount they are willing to pay for the 8 m^3 biogas plant, it will take 18.75 years to pay for the total cost. Some of the key factors influencing their willingness for biogas plants were the expenditure on other fuels and the availability of subsidies. Developing low-cost and affordable biogas plants for the rural population can increase the adoption rate.

Thirdly and related to the viability of small-scale biogas plants in rural areas of Cameroon, this study investigated the impact of the technology on the sustainable livelihood assets of the users. Biogas technology contributed to all the livelihood assets, with the most positive contribution recorded for the financial asset due to fuelwood cost saving and the sale of digestate. Biogas technology is a viable technology for rural dwellers. In relation to the environmental impact and based on field data in rural Cameroon, a 8m³ biogas plant was able to mitigate an average of 2,866 tons of CO_2 equivalent (tCO_2e) per year. Based on this analysis, integrating biogas technology in rural livelihood projects such as pig, poultry, and cattle support projects implemented by the Ministries of Agriculture and Livestock can increase the viability of the technology.

Fourthly and based on the analysis of the factors influencing households' choice of small-scale biogas plant size in rural areas of Cameroon, the users adopted based on household income, availability of feedstock, water, and subsidies (available opportunities). This resulted in different pathways in which the technology can be sustained including the productive use of biogas, cost-sharing to reduce the financial burden on the adopters and a pathway that empowers the vulnerable population to obtain and sustain their biogas plants. The productive use pathway has the highest potential for sustainability.

Finally, the causes of the slow transition to biogas energy in rural areas of Cameroon in Cameroon. This was aimed at identifying the changes needed to develop a functional national biogas innovation system. The technological innovation systems framework was used for the analysis. Results show that the main systemic problems to overcome are a poor institutional setting, lack of legitimacy, weak biogas actor-network, inadequate funding and farmers' technical capacity to sustain the technology.

Appendices

Appendix 1. Complete list of publications

Ketuama CT, Roubík H. 2025. Exploring the causes of slow biogas energy transition in rural areas of Cameroon: A technological innovation systems approach. Renewable Energy, 241, 122269. doi: 10.1016/j.renene.2024.122269.

Ketuama CT, Mazancová J, Roubík H. 2022. Impact of Market Constraints on the Development of Small-scale Biogas Technology in Sub-Saharan Africa: A Systematic Review. Environmental Science and Pollution Research, 0123456789. doi: 10.1007/s11356-022-22262-y.

Ketuama CT, Roubík H. 2024. Economic viability and factors affecting farmers' willingness to pay for adopting small-scale biogas plants in rural areas of Cameroon. Renewable Energy, 230, 120895. doi: 10.1016/j.renene.2024.120895.

Balgah RA, **Ketuama CT**, Ngwabie MN, Roubík H. 2023. Africa's Energy Availability-Deficiency Paradox: Lessons from Small-scale Biogas Technology and Policy Implications. Environment, Development and Sustainability. doi. 10.1007/s10668-023-03810-z.

Roubík H, Lošťák M, **Ketuama CT**, Procházka P, Soukupová J, Hakl J., Karlík P, Hejcman M. 2022. Current coronavirus crisis and past pandemics - What can happen in post-COVID-19 agriculture? Sustainable Production and Consumption, 30, pp.752–760. doi: 10.1016/j.spc.2022.01.007.

Roubík H, Lošťák M, **Ketuama CT**, Soukupová J, Procházka P, Hruška A, Hakl J, Pacek L, Karlík P, Menšíková LK, Jurasová V, Ogbu CA, Michal H. 2023. COVID-19 crisis interlinkage with past pandemics and their effects on food security. Globalization and Health, 19, 52. doi: 10.1186/s12992-023-00952-7.

Mukisa PJ, **Ketuama CT**, Roubík H. 2022. Biogas in Uganda and the Sustainable Development Goals: A Comparative Cross-Sectional Fuel Analysis of Biogas and Firewood. Agriculture, 12, 1482. doi: 10.3390/agriculture12091482.

Appendix 2: **Conferences attended**

Ketuama CT, Mazancová J, Roubík H. 2022. Assessment of biogas quality across rural household biogas plants in Cameroon. Proceedings of 22nd International Multidisciplinary Scientific GeoConference SGEM 2022. Vienna, Austria. doi:10.5593/sgem2022V/4.2/s18.04.

Goncharenko O, Hrynevych O, Pereira OP, **Ketuama CT.** 2021. Concept approach for measuring solidarity economy in agriculture. Selected papers of the International Scientific Conference on “Contemporary Issues in Business, Management and Economics Engineering 2021”. doi: 10.3846/cibmee.2021.614.s.

Ketuama CT, Mazancová J, Roubík H. 2022. Socio-technical challenges of the implementation of small-scale biogas technology in rural areas of Cameroon. Tropentag conference 2022. September 14 - 16, Prague, Czech Republic. Theme of the conference: "Can agroecological farming feed the world? Farmers' and academia's views".

Ketuama CT, Mazancová J, Banout J, Roubík H. 2020. PESTEL Analysis of the Development of Small-Scale Biogas Technology in Sub-Saharan Africa: A Systematic Review. Tropentag 2020, September 9 - 11, virtual conference, Germany. Theme of the conference: "Food and nutrition security and its resilience to global crises".

Goncharenko O, **Ketuama CT**. 2021. Cooperation among farmers in pandemic conditions: Solidarity Economy Aspects: Case of Czech Republic and Ukraine. 2nd Multidisciplinary Conference for Young Researchers (MCYR). Sumy, Ukraine. Theme of the conference: Sustainable Development Trends and Challenges under COVID-19.