Norwegian University of Life Sciences
School of Economics and Business

Philosophiae Doctor (PhD)
Thesis 2023:15

Market development for a sustainable transition to bioenergy in Uganda

Markedsutvikling for en bærekraftig omstilling til bioenergi i Uganda

Irene Namugenyi

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Ås (2023)

Thesis Number. 2023: 15

ISSN: 1894-6402

ISBN: 978-82-575-2044-1

Dedication

To the memory of my late uncle's wife, Mrs Henerita Kayaga Mayanja, whom the Lord called on 13th January 2013

With a big heart, you took up the responsibility of mothering me and my sister Beatrice Namugalu Kalyesubula after our mother's demise when I was only 3 years of age. Your words of encouragement are still fresh in my mind and have pushed me to do a PhD. Words like "I never went to school but my sister-in-law's children must get an education". "Study hard for a bright future and become women of value to society". Eternal rest grant unto you for all the sacrifices you made to raise me into a great woman.

I miss you and continue to RIP,

To my dearest husband Mr Stephen Anecho, you always encouraged and supported my career, you managed our home without complaining while I was away because of our love.

My wonderful children; Daniel Favor Mpungu Ssekalaala, Damita Natalia Kisa, Dante Christian Anecho, Declan Tobit Anecho and Danica Tiffany Thiwe. You allowed mummy's love to be a million miles, you always prayed for me and put a smile on my face during tough times.

I love you so much.

Irene Namugenyi.

Acknowledgements

To God be the glory, Ebenezer. I have been mentored and inspired by many good-hearted people. First, I thank my late mother Catherine Nakisozi (RIP) for giving me life and loving me. I still miss you mum; you missed seeing your last-born daughter turn into a great woman. Second, I appreciate so much my mother's brother and his wife, now the late Mr and Mrs Mayanja, for accepting to be my parents and providing for me when my dearest mother passed on. I will forever remember your love and continue to RIP. Third, I thank so much my cousin Mr Balamaze Henry Muguluma Mayanja and his wife Mrs Edith Balamaze and Cousin Andrew Mbiro for all the physical, mental, moral, and financial support throughout my education journey. To my sister Beatrice Namugalu Kalyesubula and my cousin Christine Nakabiri; thank you so much for loving me and always standing up for me whenever I need you.

To my dearest husband, Mr Stephen Anecho, thank you for keeping our children to allow me to pursue this PhD. My children Daniel Favor Mpungu Ssekalaala, Damita Natalia Kisa, Dante Christian Anecho, Declan Tobit Anecho and Danica Tiffany Thiwe, thank you for loving, praying and caring for me. Declan, leaving you at 11 months was a tough decision, Danica my last daughter giving birth to you along my PhD was very tough, but you brought so much Joy and new life, especially during the COVID-19 lockdowns. I am forever grateful to you, my lovely family. I also thank my in-laws; Ms Joyce Grace Kermu (mother-in-law) and the late Okethi Valeriano (father-in-law). My brothers-in-law; Paul Oweka and Allan Conikane and your wife Dorothy Najjingo. You all loved me and took good care of my children in my and their father's absence.

I always dreamt of becoming a professor, but I did not know how to make it. By completing this PhD, I foresee light at the end of the tunnel. However, this success has come with great support from Prof. Joachim Scholderer who has been my main supervisor. Your constructive criticisms, comments, and in-depth discussions have shaped my career and made me more zealous to pursue my professorship dream. I am also grateful to Prof. Ståle Navrud, my co-supervisor for the constructive comments, discussions and timely responses to my work which have made me move fast to complete my PhD. Many thanks go to Prof. Lars Coenen from Mohn Centre for Innovation and Regional Development, Western Norway University of Applied Sciences, for introducing me to Innovations and sustainability transitions research and supervising my research work. To Prof. Joseph Mpeera Ntayi, the Dean Faculty of Management Science, Makerere University Business

School (MUBS); thank you for introducing me to research and academia, and for continuously mentoring my research career. Further appreciation goes to Dr Livingstone Senyonga for supporting my search for PhD positions and helping me to settle in Norway.

My gratitude goes to the Norwegian government, through NORHED/NORAD, for funding the capacity-building program in Energy economics at MUBS, which has facilitated my PhD. I appreciate the MUBS management for granting me a study leave. I extend my gratitude to the management and staff of the School of Economics and Business (HH). Particularly to Prof. Gro Ladegård, Prof. Ragnar Øygard, Prof. Frode Alfnes, Berit Pettersen, Lise Thoen, Kirsti Pettersen, and Reidun Aasheim. You created an enabling research environment.

An African proverb goes, "*If you want to go fast you go alone, if you want to go far you go together*" (Martha Goedert, 2016). Several people have supported me along this PhD journey to this end. To my friends, Dr Sarah Tione from Malawi, thank you for; orienting me to the PhD; reading and critiquing my work, and guidance. I recall our late-night discussions and your mental, spiritual, and physical support that uplifted me during hard times. My flatmate and friend Anita Nyampala Okoko, you spared your precious PhD time to take care of my Danica to enable me to work and rest. I am forever grateful. My other flatmates Gabreyohans Tesfaye, and Grace Tione thank you for your patience, kindness, and support. To my office mates Mikaella Zitti and Wuddaise Dereje Bekele, you have been extremely supportive and kind to me. My other friends that became family in Norway; Fiona Akinyi Oguta, Doreen Auma, Sarah Wangui Muiruri, Miria Nakamya, Micah L. Abigaba, Esther Kemigisha, Austine Njoh, Lawrence C. Ngowi, Elone Elvistone Kanzoedie, Oheniba and Belinda Agyei, and Jethro Vidal Agyei, thank you for your wisdom and time. Appreciation to my Ugandan friends that always cared for me; Dr. Saada Kimuli, Dr. Diana Ntamu, Lydia Nakamalila, Allen Sanyu, Grace Sibeke, Josephine Bukirwa, Mariam Nakate, Robert Muwanga, Andrew Kiza Ssemakula, and my childhood friends Dorothy Katende, Ethel Nakibuule, and Prossy Nabweteme Dibya, you have all diversely contributed to my success.

Finally, I thank the data collection team, Dorothy Najjingo, Beatrice Namugalu, Daina Nakubulwa, and Bwabye Morris for the teamwork and good data.

May God reward each one of you.

Ås January 2023
Irene Namugenyi

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Summary

Access and use of clean energy persist as a grand societal challenge in Sub-Saharan Africa (SSA) without obvious solutions. This adversely affects other social-technical systems of society like health, education, climate change, environmental conservation, and the economy. This poses a further challenge to the energy transition process, which requires substituting mature, inefficient, and unsustainable biomass technologies with clean alternatives. Thus, exploring the means to address this challenge is of interest to researchers in energy-innovation policy and innovation-sustainability transition for the development and transformation of communities in SSA. To address this challenge, this thesis *investigates and elaborates on how developing countries like Uganda can scale up appropriate bioenergy technology transitions*. This objective was achieved using four interrelated research papers on two themes. Theme one includes papers 1 and II analyzing the incumbent clean cooking bioenergy systems. The theme aims at identifying windows of opportunity for a sustainable bioenergy transition. Theme two comprising papers III and IV explore how the identified niches could be exploited for a sustainable transition to bioenergy.

The first paper is titled *"Do biomass technology innovations improve subjective well-being? Traditional versus Improved cookstoves in Uganda"*. It investigates whether biomass innovations improve households' subjective well-being by comparing traditional with improved cookstoves. Using survey data, results show improved cooking technologies to break households' intangible cooking-cultural ties, which lowers their subjective well-being.

The second paper is titled *"Unsustainable cooking culture: the effect of food preparation routines and improved cookstoves on biomass energy use in Uganda"*. The paper examines the energy efficiency associated with improved cookstoves under traditional cooking routines. Results reveal that Uganda's traditional cooking routines devour the efficiency associated with improved cookstoves if used under similar routines.

The third is titled "*Realizing the transition to bioenergy: Integrating entrepreneurial business models into the biogas socio-technical system in Uganda"*. The paper assesses the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit. Using a Transitional Model Canvas and a Feasibility study, results show that biogas has entrepreneurial potential and can improve energy supply and access in developing countries.

The fourth paper is *"Valorisation of biogas for market development and remission of "environmental nuisances" in Uganda"*. The paper explores the strategies for valorising biogas to increase its commercial marketability and reduce its contribution to environmental damage. Results from pilot production and survey data reveal an existing potential for the biogas business but currently its quality is lacking and associated with emissions of the potent greenhouse gas methane.

This thesis is founded on entrepreneurship and innovation discipline contributing to innovation and sustainability transitions research. It is empirical and action-oriented following an effectuation approach applying mixed methods on mixed data sources. Generally, this thesis contributes to addressing the UN Sustainable Development Goal (SDG) 7 “Ensure access to affordable, reliable, sustainable and modern energy for all”, with multiplier effects on other SDGs.

Sammendrag

Adgang til og bruk av ren energi fortsetter på være en stor samfunnsutfordring i Sub-Sahara Afrika (SSA) uten åpenbare løsninger. Dette har en negativ effekt på andre samfunnsområder som helse, utdanning, klimaendringer, miljøvern og økonomien. Dette skaper ytterligere utfordringer for energiomstillingsprosessen, som krever substitusjon av modne, ineffektive og ikke bærekraftige bioenergi teknologier med rene alternativer. Derfor er gransking av måter å håndtere denne utfordringen av interesse for forskere på innovasjon innen energi og bærekraft for utvikling og transformasjon av lokalsamfunn i SSA. Denne avhandlingen adresserer denne utfordringen ved *å undersøke og utdype hvordan utviklingsland som Uganda kan skalere opp omstillingen til tilpassede, bioenergi-teknologier*. Dette målet ble oppnådd gjennom å bruke fire relaterte artikler på to temaer. Tema 1 omfatter artikkel 1 og 2 som analyserer rene, bioenergibaserte matlagingssystemer. Dette temaet har som mål å identifisere mulighetsvinduer for bærekraftig omstilling til bioenergi. Tema 2, som består av artiklene III og IV, utforsker hvordan de identifiserte nisjene kan utnyttes for en bærekraftig omstilling til bioenergi.
Den første artikkelen har tittelen *"Do biomass technology innovations improve subjective well-being? Traditional versus Improved cookstoves in Uganda"*. Det utforsker hvordan biomasse innovasjon forbedrer husstandenes subjektive velvære ved å sammenligne tradisjonelle med forbedrede ovner for matlaging. Data fra spørreundersøkelser viser at forbedrede ovner bryter husstandenes bånd til den imatrielle kulturarven tradisjonell matlaging representerer, og det reduserer dere subjektive velvære.

Den andre artikkelen har tittelen *"Unsustainable cooking culture: the effect of food preparation routines and improved cookstoves on biomass energy use in Uganda"*. Denne artikkelen undersøker energieffektiviteten til forbedrede ovner ved tradisjonelle matlagingsrutiner. Resultatene viser at Ugandas tradisjonelle matlagings-rutiner spiser opp effektiviteten til forbedrede ovner når de brukes til samme type matlaging.

Den tredje artikkelen har tittelen "*Realizing the transition to bioenergy: Integrating entrepreneurial business models into the biogas socio-technical system in Uganda"*. Dette paperet vurderer gründrerpotensialet og mulighetsrommet for å utvikle et mobilt system for å rense og tappe biogass i bærbare sylindre for bredere konsum og nytte i samfunnet. Resultatene fra bruk av "Transitional Model

Canvas" og en Mulighetsstudie viser at biogass har gründerpotensiale og kan forbedre tilbudet og tilgangen til energi i utviklingsland.

Den fjerde artikkelen har tittelen *"Valorisation of biogas for market development and remission of "environmental nuisances" in Uganda"*. Denne artikkelen utforsker strategier for å utvikle verdipotensialet for biogass ved å øke det kommersielle markedspotensialet og redusere dens negative miljøpåvirkning. Resultater fra pilotproduksjon og spørreundersøkelser avslører et eksisterende foretningsutviklingspotensiale for biogass, men dets kvalitet mangler nå og den medfører utslipp av den potente drivhusgassen metan.

Denne avhandlingen er basert på entreprenørskap og innovasjon, og bidrar til forskningen innen innovasjon og bærekraftig omstilling. Den er empirisk og aksjonsrettet, og følger en "effectuation"-tilnærming ved å anvende en blanding av metoder og av datakilder. Generelt bidrar denne avhandlingen til å adressere FNs bærekraftsmål nr. 7 "Sikre tilgang til pålitelig, bærekraftig og moderne energi til en overkommelig pris for alle", med ringvirkninger for andre bærekraftsmål.

1.0 Introduction

Seven (7) years remain to achieve Sustainable Development Goal (SDG) 7: universal access to affordable, reliable, and modern energy services. However, the current levels of innovation and investment in clean energy services and technologies are not sufficient to reach the 2.4 billion people who currently lack access to clean energy solutions around the world (Zhang, 2022). For instance, about 85% of the population living in sub-Saharan Africa has persistently had limited access to clean energy (IEA et al., 2021; Mukoro et al., 2022; NPA, 2020). This situation was further worsened by the COVID-19 pandemic and the increased fuel prices caused by the geopolitical war between Russia and Ukraine. Access to clean energy is by far one of the major challenges facing sub-Saharan African countries and/or developing countries with no obvious ways of addressing it in the very short term (Markard et al., 2020). This challenge has further had adverse effects on other socio-technical systems of society like health, education, climate change, environmental conservation, and the economic system (Lindgren, 2020).

A further challenge concerns the energy transition phase (society transformation), which includes the phase-out of mature and unsustainable solid biomass technologies to pave way for clean energy solutions. For example, the phasing out of the traditional 3-stone and the first generation of inefficient improved cooking technologies that have not helped to reduce solid biomass consumption in developing countries (Nepal et al., 2011), and to pave way for renewables like biogas. It is thus important to exponentially increase efforts to address this fundamental development challenge to achieve SDG 7, in the fastest most equitable way possible. To phase out the use of mature technologies, today, we see an accelerating diffusion of renewables and a decline of existing technologies such as coal and nuclear around the world (Markard et al., 2020). In the developing countries, we also see an increase in the uptake of solar and biogas solutions although these are still insufficient in this part of the world (Zhang, 2022).

Markard et al. (2020) suggest that to address access to clean energy challenges in developing countries, technology should enter a new phase in which emerging innovations accelerate and contribute to broader system transformations. IEA et al. (2021) further posit that there is an urgent need to scale up investment in innovative clean technologies through entrepreneurship and market development activities. Additionally, Semple et al. (2014) contend that the economic costs of relying on polluting fuels and technologies make a strong case for technological innovations if countries are to accelerate energy transitions. In line with this argument, there is an increasingly global movement and interest in developing renewable energy markets to target a transition from fossil and forest based fuels to clean and sustainable energy resources (Anenberg et al., 2013; Mazorra et al., 2020). Therefore, in many countries, policies promoting sustainable transitions to clean and renewable energy are in effect and market development is a major driver behind these policies (Ottosson et al., 2020; Wennberg & Sandström, 2022). Owing to this movement, while focusing on the case of Uganda, I ask the following questions:

1. How should society turn around the existing energy socio-technical system?
2. Which regimes should be transformed to increase access to clean energy in developing countries?
3. How can mature, inefficient and unsustainable technologies be phased out of society in a way that addresses social, economic, and environmental sustainability?
4. How can this phase-out be accelerated?

These questions create a case for this thesis with the main objective *to investigate and elaborate how developing countries like Uganda can scale up appropriate bioenergy technology transitions*. This objective is investigated using four (4) different but interrelated empirical research studies which build up this thesis.

The four research studies used an action oriented research (Wittmayer et al., 2014) and mixed methods with mixed data sources (Maxwell, 2012), supported by sustainability transitions (ST) (Köhler et al., 2019) and business model innovation (BMI) theories (Osterwalder et al., 2011). The first and second paper analyzes the existing (incumbent) clean cooking solutions to identify systems weaknesses and niche opportunities for Uganda's clean energy systems' development. Papers three and four explore how the niches identified in paper one and two could be exploited to increase access to clean energy and achieve a sustainable energy transition in Uganda. The underlying motivation of this research thesis is the recognition that the energy and innovation policy for Uganda has given less attention to market development solutions as a driver for sustainable energy transitions. Sustainability transition scholars have also given less attention to market development activities as an accelerator of transitions in social-technical systems.

Furthermore, the sustainability transition literature focuses less on action research as a method of addressing societal challenges to which this research contributes. Similarly, Köhler et al. (2019) argues that it is important to integrate practice into theoretical approaches for transitions to be successful in bringing radical change to society. Besides action research helps to analyze the current state of the art of societal challenges in preparation for smooth transitions (Smith, 2010).

2. The clean energy market in Uganda

Uganda does not have a specific policy targeting bioenergy production, but, has a renewable energy policy (MoEaMD, 2007), although, this has not been revised since 2007. However, the overall energy policy for Uganda includes an objective *"to promote the development of the liquid bioenergy market and provide incentives for private sector investment"* (MoEaMD, 2019). This objective supports the promotion of bioenergy production through market development pathways such as private investment in entrepreneurship activities. Furthermore, the policy acknowledges a challenge of depleting solid biomass resources that the current improved technologies are unable to overcome. On the other hand, Uganda is richly endowed with renewable energy resources (manure and municipal waste, solar, water bodies for hydro-electricity generation, wind, and geothermal) for energy production and the provision of energy services (Kees & Eije, 2018; MoEaMD, 2019). These resources, however, remain largely unexploited, because of the perceived technical and financial risks, coupled with low innovation capabilities and weak innovation policies (Namugenyi et al., 2022). According to IEA et al. (2021), Uganda's energy balance comprises primarily 88% biomass consumed through firewood, charcoal, and crop residues and used on inefficient (traditional) technologies. Hydroelectricity contributes approximately 2%; while fossil fuels (oil products) account for 10% of the national energy mix. Transport consumes 90% of imported oil products whereas kerosene use in households consumes 6%. By September 2021[1] the rate of electricity connectivity access was 38%, with a total installed generation capacity of 1346.6 MW[2].

Uganda has a huge supply gap for clean energy with a high potential for biogas production (UBOS, 2015). From a population of 42 million people, only about 38% of the country is

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[1] https://www.africanreview.com/energy-a-power/power-generation/uganda-to-increase-electricity-access-in-rural-communities

[2] https://www.era.go.ug/index.php/stats/generation-statistics/installed-capacity

connected to the grid and over 30 million people lack access to clean energy (Elahi, 2019; UBOS, 2021). This means there is a huge market potential for the supply of off-grid clean energy services like biogas. According to Kruger et al. (2018), Uganda ranks tenth in sub-Saharan Africa (above the regional average) regarding ease of doing business, expected market growth, economic freedom, and global competitiveness. Uganda's capital market is also reasonably well-developed and is actively accessed by banks and insurance companies. Additionally, energy policy regimes in Uganda support the increased role of the private sector in power production, operations and future energy developments (MoEaMD, 2019). The renewable energy policy also aims to promote the conversion of municipal and industrial waste to biogas energy (MoEaMD, 2007). With such regime dynamics, clean energy would have a high potential to thrive in Uganda.

However, despite the limited clean energy supply coupled with questions of how to provide affordable, safe and clean energy to a low-income rural and urban population (UN General Assembly, 2015), clean solutions like biogas are considered to be pro-poor renewable energies in Uganda and thus not valorised (Bluemling et al., 2013). Policy structures for promoting biogas in Uganda have thus focused on providing biodigesters (subsidized or free of cost) to poor farming communities to reduce the use of firewood and kerosene which is the main fuel for cooking and lighting respectively (Okello et al., 2013). Similarly, private entrepreneurs targeting biogas production focus business on the construction of biodigesters with limited knowledge of biogas valorization activities like fermentation and upgrading processes (paper 4 in the thesis). More to that, policy programs concerning biogas production are implemented by a small group of actors from, non-government organizations (NGOs) and private companies with regulation and subsidization from the government Ministry of energy and Environment.

Besides cost subsidization, the government and NGOs use a "*free of cost*" and "*free of service*" model to implementing biogas solutions; households do not incur the cost of biodigester acquisition which causes them to easily dis adopt the technology (Lwiza et al., 2017). This model used to implement and promote biogas solutions in Uganda is thus poorly developed to properly address economic growth and attract direct income realization for households. The model is also faced with institutional lethargy in technology monitoring and does not attract investment from financial institutions because the technology is in the hands of the poor who have no collateral to facilitate loan servicing (Clemens et al., 2018; Namugenyi et al., 2022). Furthermore, the model has been inadequate in accelerating access to clean energy and phasing out mature inefficient technologies in Uganda; thus calling for fundamental long-term changes referred to as sustainability transitions (Köhler et al., 2019). The policy has also failed on the large-scale application which leaves unexploited niche opportunities in Uganda's biogas socio-technical system. These opportunities could, however, be exploited through new business model orientations like integrating entrepreneurial strategies and valorizing biogas for market development as discussed in Paper 3 and 4 in the thesis respectively.

According to the MoEaMD (2019) and UNDP (2020), and anecdotal evidence in this thesis, transitions to clean energy technologies in Uganda are challenged by several factors. These factors include diverse cultural discourses regarding energy use, low levels of innovation, weak implementation of renewable energy policies and limited market development solutions for existing clean energy technologies. Cultural discourses have particularly influenced the promotion of clean technologies like the improved cook stoves although these are now mature, inefficient, and have neither helped reduce energy cost nor energy use (Nepal et al., 2011) and (paper 2 in this thesis).

Zhang (2022) and IEA et al. (2021) report that limited access to clean energy is still a real-world and grand societal challenge requiring innovative and action-oriented approaches aimed at accelerating radical change. However, for such change to occur, it is important to understand the existing (incumbent) energy systems and the factors that influence them (Baumgartinger-Seiringer, 2022; Namugenyi et al., 2022). This understanding helps transition actors to identify niche opportunities that could be exploited to pave way for innovations that out-compete incumbents, a process referred to by Schumpeter as "creative destruction" (Geels & Kemp, 2007; Turnheim & Sovacool, 2020). Liao et al. (2021) found that data on the sources of energy technologies from which households are transitioning and the energy portfolios households use should be clear and available to aid faster energy transitions. Therefore, a comprehensive analysis of the type of energy technologies recommended for society transition is vital for a clear understanding of how transition outcomes will benefit society. Additionally, the transition theory explained in the next section helps further support the understanding of energy transitions, how they could be implemented in developing countries and which implications they will have on society.

3. Theoretical foundations and conceptual framework

The analysis of Uganda’s clean energy market reveals that access to clean energy is still a major societal challenge that demands rigorous and aggressive market development structures to bring fundamental societal change. This will require changes in different elements like legal and policy frameworks, business, and users’ social and cultural practices (Markard et al., 2020). The legal and policy framework elements involve policy objectives which are also the transitional goals of focus during the change process. These elements are used by entrepreneurs to effectuate and accelerate energy transitions. Effectuating transitions focus on using a set of given means to select between possible effects that can be created with that set of means (Sarasvathy, 2001). Effectuation brings together transition actors, actor networks and activities to efficiently use the available resources to cause a radical change in society (Geels, 2011; Markard et al., 2020).

3.1. Market development in the context of transitions

Market development (MD) is an important component of transitions because it emphasizes the role of market segments, transactions, and end-user value propositions of technological innovations (Kamat et al., 2020). Without market development, new technological innovations cannot break through or even improve society’s well-being (Boon et al., 2020). For this reason, MD is considered a valorisation activity for social technical systems. This activity, however, requires effectuated means aimed at communicating the value proposition of innovations to customers for monetary exchange (Kamat et al., 2020). From this context, market development in sustainability transitions involves three main stages that include learning the new technology, expanding the market to new spaces and sales growth through scaling up (de Vasconcelos Gomes & da Silva Barros, 2022). de Vasconcelos Gomes & da Silva Barros further indicate that these stages might involve controversy and conflicts from incumbent actors (actors from existing markets) and disruption of incumbent market positions. Existing market actors can contest the desirability of new sustainability markets and fail to fully agree on the new sustainability value proposition and incumbent markets, which could threaten existing markets and positions.

During sustainability transitions, actors and platforms are important intermediaries as they positively stimulate market development processes by linking actors and activities and their related skills and resources (Peixoto & Temmes, 2019). Actors and platforms also connect transition visions and actor-network demands with regimes that cause socio-technical systems transformation, new collaborations within and across niche technologies, ideas, and new markets, and disrupt dominant unsustainable structures (Boon et al., 2020). From this understanding, market development pathways for sustainable products like biofuels are heterogeneous. They can focus on creating completely new spaces, extending, or abutting existing markets, or moving from one market space to another. Because of this heterogeneity, different actors are involved and individually or collectively contribute to the formation of sustainable markets (Kamat et al., 2020).

Additionally, actors such as entrepreneurs (system builders) might find it difficult to determine the right set of competencies required to effectuate all transition tasks in a social-technical system. This is where different actors (beyond private and public actors) with diverse competencies become important as they effectuate the development of new market ecosystems and create interactions through exchanges for value (de Vasconcelos Gomes & da Silva Barros, 2022; Ottosson et al., 2020). In the scenario of introducing radical innovations to the market, niche and regime actors' cognitive perspective focuses on the construction of dominant and legitimized regimes to control the market (Boon et al., 2020). State actors may focus on funding collaborations among a set of organisations instead of technologies to generate a pivotal value proposition and provide moral support and cognitive legitimacy (de Vasconcelos Gomes & da Silva Barros, 2022). The system builders may focus on the micro-level of transitions and contribute to market development through collective actions (Kamat et al., 2020). This kind of diverse activity structure, where each actor or actor-network uses different means to individually or collectively contribute to market development in sustainability transitions justifies an effectuation approach to transitions (Read et al., 2016; Sarasvathy & Dew, 2008). Effectuation consists of a set of principles, including strategic alliances, affordable losses, exploitation of contingencies, and controlling an unpredictable future, that is more action-oriented than spending resources on extensive planning activities (Sarasvathy, 2001).

Furthermore, market development in the context of transitions is a policy instrument (Boon et al., 2020). The instrument aims at transforming economic and social systems through the promotion of better alternatives such as conventional fuels to more sustainable biofuels. Sustainability transitions can thus be achieved through the implementation of market development solutions as policies adapted to local contexts (Köhler et al., 2019). To develop and foster markets for clean and sustainable technologies, transitional policies engage multiple actors and involve complex market mechanisms such as competition, customer acceptance, and demand in the local context entwined with global processes like sustainable development goals structures. Through refining such interlinked structures, market development processes create important intuitions about the effects of policy on market outcomes (de Vasconcelos Gomes & da Silva Barros, 2022). Concerning policy implementation, the transition literature posits that policy outcomes are shaped by the interaction of previous local technology paths, local resource and industry contexts, and national regulatory and policy cultures (Boon et al., 2020). Additionally, frequent policy changes, for instance in response to disagreements, create a policy discrepancy that impedes investment in a promising market. Given the ongoing technological development in Uganda's energy sector, enabling technological transitions through market development policy implementation is critical for a successful and sustainable transition to clean energy.

3.2. Sustainability Transitions

Sustainability transitions are complex, long-term, non-linear and slow processes of change that require well-coordinated networks of actors to identify niche opportunities and build systems that can transform society (Fallde & Eklund, 2015; Kivimaa et al., 2020; Schaltegger et al., 2022). The concept of sustainability transitions helps to analyze current societal dynamics expressed through societal challenges (Geels, 2011). Sustainability transitions involve a multitude of complex processes and practices that lead to changes in cultural, legal, and normative regimes, changes in everyday practices of organizations and consumers, social relations, and structures (Kivimaa et al., 2020). Transitions on the other hand are transformation processes in which existing structures, institutions, culture, and practices are broken down and new ones emerge (Geels, 2002; Goyal & Howlett, 2020; Köhler et al., 2019). These processes can be understood as shifts or system innovations amongst idiosyncratic socio-technical organizations surrounding not only new technologies but also changes in markets, user practices, policy, and cultural discourses as well as governing institutions (Schaltegger et al., 2022). These processes of change happening in transitions take place at three dynamic levels categorized under the Multi-level perspective framework (Coenen & Díaz López, 2010; Geels, 2002).

3.2.1 The Multi-level perspective (MLP) framework

The multi-level perspective (MLP) framework argues that transitions emerge through dynamic processes within three analytical levels. That is, (1) niches, from which radical innovations emerge. (2) Social-technical regimes (institutional structures like rules) of existing systems that protect the relationship between the different transition actors, and (3)The social-technical landscape (e.g., climate change mitigation) that influences innovation activities of the niche and regime actors (Geels & Kemp, 2007). As they navigate transitions, actors may interpret, enact, fight, negotiate, search, learn, and build coalitions within the social-technical landscape (Köhler et al., 2019). Ensuing interactions between niches and regimes occur on several magnitudes such as markets, cultural dynamics, technologies, and regulations. Part of influencing transitions is thus, the creation of protected spaces (niche opportunities), activities and actor networks to innovate and search for alternative solutions to societal challenges (Jacobsson & Bergek, 2011; Kivimaa et al., 2020).

Coenen and Díaz López (2010) assert that technological niches and socio-technical regimes consist of similar elements but differ in scope and stability; the former is more diverse and heterogeneous in rules and innovation activities. Regimes encompass a highly complex structure that includes scientific knowledge, engineering practices, production process technologies, product characteristics, skills, procedures, established user needs, institutions, and infrastructures. The organisation of this complex offers stable rules that allow actors to coordinate activities, to maintain and improve the socio-technical systems through incremental innovations. On the other hand, the nature of niches makes them unstable thus causing disruptive and more radical innovations (Fallde & Eklund, 2015). The socio-technical landscape consists of slow-changing external factors that condition the interaction of niche and regime activities (Köhler et al., 2019; Markard et al., 2012). Therefore, the MLP helps to explain the transformation process happening in socio-technical systems. In Figure 1, I use the three MLP levels to explain how the sustainability transition theory supports the studies in this thesis. In the figure, the MLP consists of an incumbent system (existing system), that is disrupted for a new (niche) system to emerge. Disruptions within the incumbent system create niches that a small group of actors known as systems builders (entrepreneurs) exploit during the transition process to cause radical change (Fallde & Eklund, 2015; van Rijnsoever & Leendertse, 2020). Actors exchange resources, create networks and markets and form productive supply chains using business models (Fallde & Eklund, 2015; Massa & Tucci, 2013).

3.2.2. Business model innovation (BMI)

A business model refers to a plan for the successful operation of a business, identifying sources of revenue, the intended customer base, products, and details of financing (Massa & Tucci, 2013). While building strong sustainability transition systems, Sarasini and Linder (2018) and Namugenyi et al. (2022) argue for the innovation of superior business models to work as drivers or enablers of transitions. Strongly designed business models help to penetrate societal dynamics and identify consumer preferences and offer superior solutions to grand societal challenges. (Schaltegger et al., 2022). The rationale for pursuing strong business models is that incumbent system markets are easily destabilized which paves way for niche opportunities and the emergence of radical innovations. Business models also allow socio-technical systems to create, capture and deliver economic and social value to users. Through business models, actors (systems builders) can establish customer segments and the product to offer, the activities to enable the product to reach the customers, the resources needed to produce and deliver the product and the capabilities available to produce the product that will create value for the customers (Figure 1).

Therefore, although sustainability transition is the domain theory for this thesis, the concepts from the business model innovation theory are also important when exploring how actors can proactively engage with social-technical systems to address societal challenges (Sarasini & Linder, 2018). Additionally, the two theories complement each other in such a way that the transition theory comprehensively explains the process of change, as the business model innovation theory helps to enact the change in socio-technical systems (Sandberg & Alvesson, 2021). Sustainability transition theories provide a framework in which key elements of the multi-level perspective (Geels, 2002) interact with the contents of the business model canvas (Osterwalder et al., 2011) to analyze incumbent systems and identify niche opportunities ate are exploited by entrepreneurs in the transition process. Therefore, a combination of the two theories is a practical way of addressing societal challenges which makes this study action-research oriented (van Rijnsoever & Leendertse, 2020; Wittmayer et al., 2014). Building on this discussion Figure 1 presents the schematic conceptual framework for the sustainable energy transitions in Uganda.

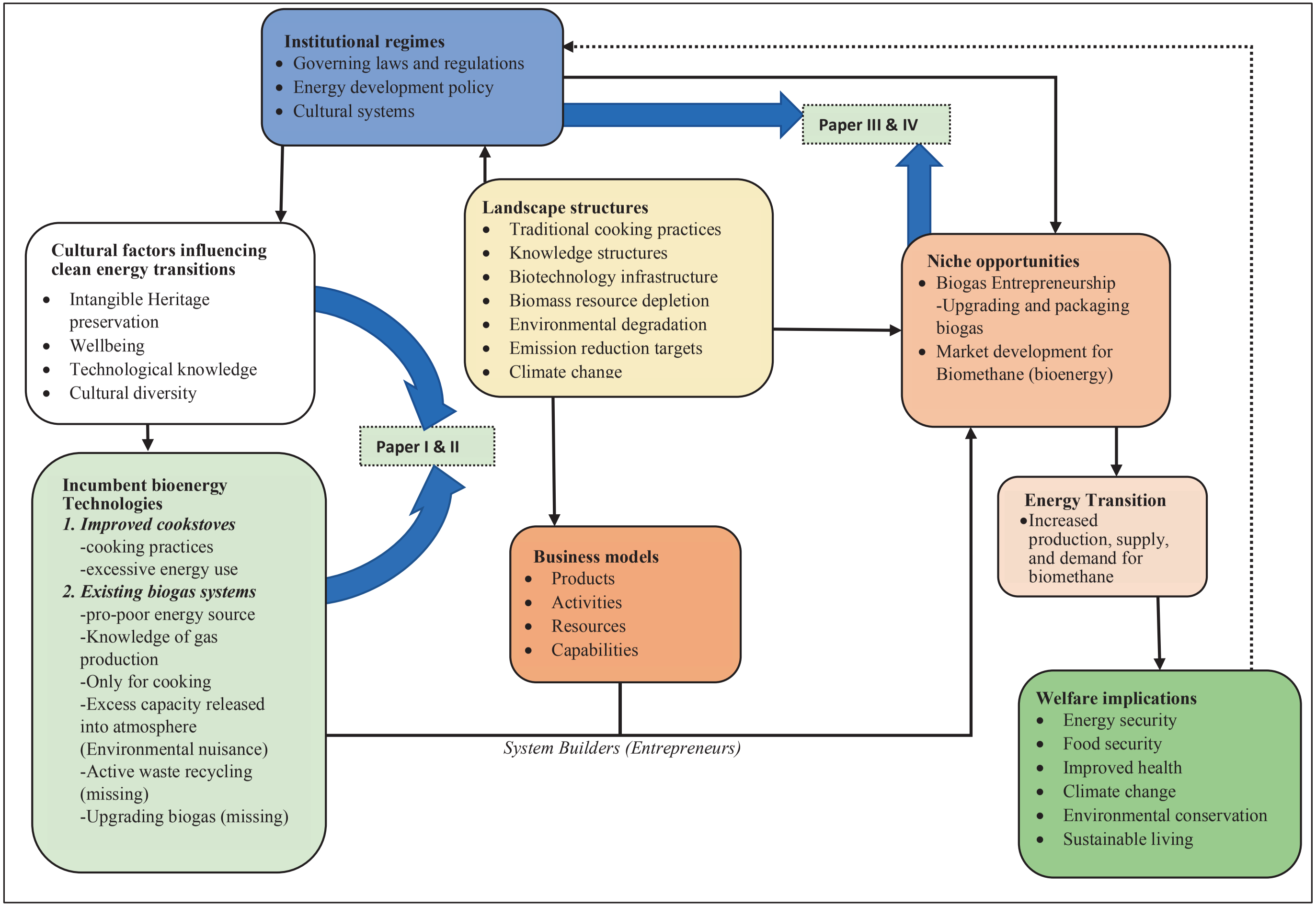

Figure 1: Conceptual Framework

The conceptual framework in Figure 1 shows that regimes, landscape structures, and niches valorise sustainability transitions. The institutional regimes include the governing laws and regulations, energy development policies and the cultural systems instituted to facilitate resource allocation in the different energy systems like bioenergy, hydro production, and biomass renewal. The energy development policy includes support strategies for improving the bioenergy sector like subsidies for increased private sector investment in the liquid bioenergy market for future energy development. Cultural systems represent the existing values, beliefs, and norms (intangible heritage) carried by society that influence the promotion, adoption, and diffusion of sustainable technological innovations. In this thesis, the conceptual model presents the specific factors that define the cultural system that can support or inhibit transitions. These specific cultural factors can influence society's decisions on which technology to use from the clean energy technologies available.

From Figure 1, the existing (incumbent) clean bioenergy technologies available in Uganda are improved cookstoves (ICS) and biogas energy systems. The two bioenergy systems comprise several attributes that actors could analyze to skim for windows of opportunity (niches), which they exploit using business models as they build a new system of change (niche system). As entrepreneurs exploit niches, business models enable them to identify the right products, create business activities, find the necessary resources and capabilities needed to create value for society and achieve radical change (Bolton & Hannon, 2016; Sarasini & Linder, 2018). As niche actors search for opportunities, they may disrupt incumbent systems (Mukoro et al., 2022; Santos et al., 2009). For example, when niche actors valorize biogas and increase their market share, the market for improved cookstoves and solid biomass may significantly decline.

Figure 1 further shows that the socio-technical landscape consists of structures embedded in society that create pressure on the regime and niche systems (Schaltegger et al., 2022). Such structures include inter alia, traditional cooking practices, knowledge structures, biotechnology infrastructure, biomass resource depletion, environmental degradation, emission reduction targets, and climate change. These structures can support or fail regimes targeting the improvement or destruction of incumbents and can also support or inhibit the growth of niches (van Rijnsoever & Leendertse, 2020). Landscape structures can also support or fail the business models actors might use to exploit niches. From Figure 1, when the niche opportunities have been exploited and the energy transition realized through increased production, supply, and demand for bioenergy, welfare implications for society such as sustainable living will be achieved. Welfare implications will further inform policy decisions and support the development of new institutional regimes. The theoretical framework outlined in Figure 1 was thus used to generate and support the research objectives studied in the four (4) papers of this thesis.

Considering the thick blue bold arrows in the conceptual framework, paper one analyses the dark side of innovation on households' subjective well-being. This dark side concerns households moving away from their intangible cultural cooking heritages. Paper two investigates whether improved cookstoves reduce excessive energy use and cost caused by the food preparation routines embedded in Uganda's cultural cooking traditions. Paper three assesses the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit. Paper four explores how biogas can be valorised to stand a chance as a commercial market offering and reduce "environmental nuisances" in Uganda. In the next section, I discuss the data and methods used to investigate the objectives of the four research papers.

4. Data and Methods

4.1. Data sources

The thesis is based on empirical findings and is divided into two themes that use different data sources. Theme one has two papers that use cross-sectional survey data collected between July-October 2019 from users and non-users of improved cookstoves. Uganda is divided into four regions: Central, Eastern, Northern and Western. As of 2010, the four regions are further subdivided into 134 districts. Four (4) out of twenty-four (24) districts including Mukono, Kampala, Wakiso, and Luwero were purposively sampled in the central region; the districts have the highest number of users of improved cookstoves (Statistics, 2016; UBOS, 2014). Figure 2 shows the study areas selected from the central region of Uganda. The survey targeted three (3) user segments that included (1) 169 households (2) 63 institutions (Schools) and (3) 59 restaurants. These segments according to energy use statistics are the largest users of solid biomass (UBOS, 2015). The survey instrument captured data on household cooking perceptions, considerations, and practices of using Improved Cookstoves (ICS) and Traditional Cooking Methods (TCM) with

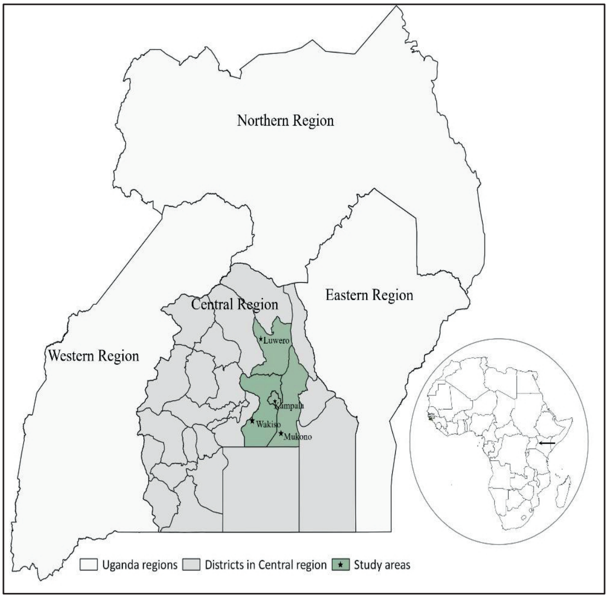

***Figure 1**: Survey areas in Central Uganda.*

related questions on traditional cooking heritages and subjective well-being. Cooking routines and energy use patterns among users and non-users of improved cookstoves in Uganda were also established. The data was collected using computer-assisted personal face-to-face interviews (CAPI). After a thorough review of the data instrument, we transformed it into a digital format using the Open Data Kit (ODK) that is installed on android tablets. From the household, the target respondent was the decision maker (household heads); the person(s) with the main responsibility for purchasing and using cooking technology.

In the data set, the amount of fuel used by the different segments was obtained in various measurement units along with the cost estimates per month. For instance, charcoal (trucks, full bags, half bags, basins, and smaller units), and firewood in trucks and bundles. Electricity was captured in Kilo watt hour, gas, and briquettes in kg. Kerosene was captured in a litter. To compute the exact amounts and prices of the fuel used in the different segments, additional data were obtained by physically weighing units of charcoal (full bag, half bag, and smaller units) and firewood (bundles), from 30 observations in kilograms (kg) and price in UGX for each unit. Measurements were obtained from five different firewood and charcoal vendors from different market locations. The averages of each category were computed and used to define the kilograms and later the megajoules in the main survey data set. To quantify the energy equivalents of these different units, we adopted energy values of unprocessed biomass and other fuels recommended by Openshaw et al. (2015). Based on REF we allocated energy values of 29.0 Mega Joules per kilogram (MJ/kg) and 18.7 MJ/kg for charcoal and firewood respectively. The energy input values were used to compute the energy cost and use equivalents of the sample segments (institutions, restaurants, and households). The information collected from all three segments was used to calculate energy use per person meal and energy cost per person meal; these were our dependent variables of interest. The qualitative findings from this survey data were used to investigate and build the discussions in papers three and four of part two of the thesis.

The second part of the thesis has two papers that investigate how the biogas niche market in Uganda could be exploited. Paper three uses multiple data sources and mixed methods. First, it uses qualitative and observation data obtained from semi-structured (key informant) interviews (where it derives its objectives) which were part of the study survey used in Papers 1 and 2, data from document analysis and feasibility study. Second, the paper uses data from a feasibility study on the availability and prices of equipment used to build biogas upgrading equipment collected in August 2020. The feasibility study data were obtained using two scenarios: the local scenario and the international scenario. In the local scenario, the data on material costs was searched and aggregated from local suppliers in Uganda. In the international scenario, the data was obtained from Alibaba an online international shopping store. Thirdly, the paper used qualitative data obtained from government documents (energy policy documents and census reports (e.g.; (MoEaMD, 2007, 2015, 2019; UBOS, 2014, 2015, 2021) and online reports on clean energy (e.g.; (IEA et al., 2021; IRENA, 2017).

Paper four used multiple source qualitative data from semi-structured interviews and pilot production obtained from a case study of a biogas plant at the National Livestock Resources Research Institute (NaLIRRI), and stakeholder interest surveys conducted from February to July 2022. The pilot production obtained data on the quality of raw biogas (input) and upgraded methane (output) produced at NaLIRRI. The data from the customer interest survey intended to establish the most promising customer targets for biogas products while the farmer's interest survey helped to assess biogas production and management from a small-scale producer perspective. The data from the small-scale producers was helpful to corroborate the findings from the pilot plant. Overall, the different data sources individually contributed to the four studies through an effectuation methodology to market development (Sarasvathy, 2001) presented in the subsequent section.

4.2. Methods

This thesis is grounded on entrepreneurship and innovation principles with a bias on innovation and sustainability transitions research. According to Shane and Venkataraman (2000) and Foss and Klein (2020) entrepreneurship involves the study of sources of opportunities; the processes of discovery (Ardichvili et al., 2003), evaluation (Shane & Venkataraman, 2000), and the exploitation of opportunities; and the set of individuals who discover, evaluate, and exploit them. In line with these views, the thesis employs an effectuation (Sarasvathy, 2001), creation (Alvarez & Barney, 2007) and an action-research-oriented approach (Wittmayer et al., 2014), involving mixed data sources and methods. Following the definition of effectuation approaches in the theoretical framework in section 3, the mixed methods and data sources were used as a set of means to study how the transition to clean energy in Uganda could be effectuated. According to Sarasvathy and Dew (2008) effectuation approaches are action-oriented and describe ways of making decisions and performing entrepreneurial actions and identifying the next best step; by assessing the resources available to achieve your goals while continuously balancing these goals with your resources and actions. Unlike causal logic, where the goal and the process to achieve the goal is predetermined and carefully planned in accordance with a set of given resources, entrepreneurial processes are naturally uncertain and risky (Foss & Klein, 2020; Sarasvathy, 2001). Therefore, effectuation provides a way of thinking about making decisions when non-predictive control is required to create products, markets, and ventures.

In the context of this study, the action-oriented approach is used to address a real-world problem, limited access to clean energy. Using the effectuation approach, the thesis analyses the incumbent clean energy system to identify weaknesses that could be exploited through entrepreneurship and market development processes and policies. Action research models are effectuated by identifying the existing societal challenge, analyzing the current state of the art to identify how the problem has been addressed before and establishing well-researched practical solutions to the problem (Smith, 2010; Wittmayer et al., 2014). The challenges that could be encountered when resolving the problem and how these challenges could be overcome to arrive at a sustainable transition are also important to earmark while using action-oriented models (Wittmayer et al., 2014). Against this backdrop, the thesis considered the following set of means and/or methods to study how access to clean energy could be effectuated in Uganda.

The first set of means (**Paper one objective**) was to investigate whether the existing clean energy technologies (improved cookstoves) have a dark side and if this dark side affected households' subjective well-being of traditional cooking practices. This objective was important to consider since it informs transition actors of how to avoid building clean energy niches that will not attract demand from users. This objective was informed by informal preliminary discussions with five (5) improved cookstove entrepreneurs organised under the Biomass Energy Technology Association (BETA). All five entrepreneurs indicated that customers have several cultural considerations for using clean technologies and this affected technology diffusion. The study was completed by analysing the cross-sectional survey data. Because well-being is a latent variable, the dependent variable (subjective well-being) was generated using Principal component Analysis (PCA) and the results were obtained using a Linear regression model.

The second set of means (**Paper two objective**) was to establish whether the cooking cultural considerations (food preparation routines); that contribute to household subjective well-being in paper one, led to excessive energy use and energy cost; and how improved cookstove influenced the expected effect. This objective was investigated using linear mixed models estimated with log cooking time, log energy use and log energy cost as the dependent variables using the cross-section survey data.

The third set of means (**Paper three objective**) explores the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit. The paper explores this entrepreneurial potential using a multimethod approach, comprising semi-structured (key informant) interviews, nonparticipant observation, document analysis and a feasibility study. The semi-structured interviews and the non-participant observations were part of the survey used in papers one and two. From the interviews and observations in the survey, households that cooked with biogas had a clean and smoke-free environment compared to households that used solid biomass (firewood and charcoal). These findings from the survey were backed by a thorough examination of documents analysis and examination. This provided background knowledge and historical insights that helped to understand how the societal challenges observed in the survey could be addressed. According to (Bowen, 2009) documents are social products of collective and organized action. They serve as action research tools to track change and development within a social system. The analysis of the results was completed using a transitional model canvas (van Rijnsoever & Leendertse, 2020); a practical tool that uses the MLP and BMI concepts to analyse transitions. The insights from the review of documents and transitional model canvas prompted a feasibility study to establish whether the materials for upgrading biogas are locally available and affordable in Uganda. The feasibility was analysed in the local Vs International scenario context.

The fourth set of means (**paper four objectives**) explores how biogas can be valorised to stand a chance as a commercial market offering and reduce "environmental nuisances" in Uganda. The environmental nuisance concerns the release of biogas into the atmosphere to relieve the pressure built up inside the biodigester. The semi-structured interview data from the pilot plant was video recorded with consent from the interviewees and transcribed; the pilot production captured input (raw biogas) and output (after upgrading the biogas) concentrations of methane (CH4), carbon dioxide (CO2), hydrogen sulphide (H2S) and oxygen (O2). Process Analytical Technology (PAT) was used to take the readings of these gas concentrations. Pilot production data was analysed using X-bar/R control charts for gas input and output concentrations. Data from the customer interest survey was analysed using Correspondence Analysis (CA) in three dimensions and jointly hierarchically clustered, using Ward's method. The customer interest survey was captured as a matrix representing product portfolios corresponding to different customer segments. The farmer's interests were investigated through informal consultations and observations. In the farmer survey, we randomly visited ten (10) small-scale biogas farmers; three (3) in Kampala and seven (7) in Wakiso district in central Uganda (see Figure 2). We also obtained secondary data (from unpublished reports) from SNV; The Netherlands development agency promoting biogas use in Eastern Africa. The data was used to study and analyse farmers' voices and perceptions of biogas production and use. This data was analysed, and the results were presented using a pie chart.

5. Scientific contributions

The four research papers in this thesis investigate and elaborate on how energy transitions could be effectuated in Uganda. The papers assess the incumbent bioenergy socio-technical system, to identify niche opportunities that are exploited to transform society through energy transitions. Following this trend, the four papers respond to the specific questions outlined; (i) how should society turn around the existing energy socio-technical system? (ii) which regimes should be transformed to increase access to clean energy in developing countries? (iii) how can mature, inefficient and unsustainable technologies be phased out of society in a way that addresses social, economic, and environmental sustainability? (iv) how can this phase-out be accelerated? In response to these questions, the thesis contributes to energy policies regarding improving the liquid bioenergy market in Uganda. Most importantly, the thesis addresses sustainable development goal (SDG) 7 with multiplier effects on other SDGs. The sub-sections below summarise the contributions from each of the four research papers in this thesis.

7.1. Paper 1: Do biomass technology innovations improve subjective well-being? Traditional versus Improved cookstoves in Uganda

Objective

Whilst previous studies explore several factors and contributions of biomass cooking technologies on society, it could be argued that they have ignored the empirical analysis and documentation of the dark side of improved cookstove technologies on household's subjective well-being (Engelbrecht, 2018; Spanakis et al., 2016). This paper aims to investigate the dark side effect of clean biomass innovations (improved cookstoves) on households' subjective well-being in Uganda. The dark side of biomass technology innovations concerns households moving away from the intangible cultural cooking heritages they have preserved for a long time. These cultural heritages contribute to households' subjective well-being (Lang & Caraher, 2001). Moving away from them can cause households to reject clean technologies thus delaying sustainable energy transitions.

Data

To analyse the subjective well-being of users of improved cookstoves in Uganda, we specifically use the survey data from 169 households. The key indicator for assessing the subjective well-being of using traditional cooking practices was the change of cooking practices from traditional to improved ones. This key indicator was: "we can change our cooking practices from traditional to improved ones." This question was part of the Likert scale questions captured on the perceptions and considerations of users of improved cookstoves in Uganda.

Analytical methods

To measure the subjective well-being of households, I used nine (9) Likert scale questions. The questions were related to traditional cooking considerations, practices, and perceptions. Out of the nine (9) Likert scale questions, I obtained a linear variable that combined all the responses using Principal Component Analysis (PCA) (Kurita, 2019). Because subjective well-being is a latent variable, and several variables can define well-being. PCA identifies the most meaningful basis to re-express and reveal the hidden structure of the nine questions. The stated questions were; 1) Cooking with open fires keeps my tradition alive, 2) I like my food cooked with open fire, 3) I eat from home (here) because the food has a distinct aroma, 4) Food cooked on an open fire has a distinct taste, 5) The way I cook is very important for my tradition, 6) I have more confidence when cooking traditional foods on an open fire, 7) A traditionally cooked meal gives me a sense of security, 8) I feel proud when eating food cooked on an open fire, and 9) To me, cooking on improved stoves connects with happiness and a feeling of well-being. Using the SWB score generated from the PCA as the dependent variable, I used a linear regression model to test a null hypothesis; Ho*: Using improved cookstoves reduces the household's subjective well-being of practising traditional cooking methods*.

Research findings

From the results, households who reported that they can change their cooking practices from traditional to improved ones; had their subjective well-being reduced by 32 percentage points. This implies that changing from traditional to improved cooking practices reduces the SWB of traditional methods related to cultural cooking values and that households in Uganda are less likely to change from such cooking practices. Results further show a significant positive effect on the households reported not having ICS on subjective well-being at a 10% significant level. Not having ICS increases the subjective well-being of households by 29.7 percentage points, ceteris paribus. This implies that using ICS move Ugandan households away from traditional ways of cooking, which reduces the well-being they attach to the intangible cultural heritage of traditional cooking.

Paper contribution

The dark side of technology is important to understand as it contributes to policy decisions on sustainable societal transformation in the clean cooking energy sector. Paper one's findings thus, add to the scarce literature on innovation for well-being and innovation for transformative change. This literature is critical to addressing grand societal challenges because it considers the well-being of technology users (Castellacci & Tveito, 2018; Martin, 2016; Schot & Steinmueller, 2018). Therefore, the implications from this paper are that “innovation for wellbeing” is a major component in transitions and it should be considered by entrepreneurs when building niches in the bioenergy sector. More to that, understanding and involving user well-being in the design of transitional models could lead to sustainable energy use, sustainable development and sustainability transitions in other sectors of developing economies (Li et al., 2018). The main takeaway from this paper for transition actors is that sustainability transitions may fail if society feels that certain intangible cultural heritages will be lost by adopting clean technologies.

7.2. Paper 2: Unsustainable cooking culture: the effect of food preparation routines and improved cookstoves on biomass energy use in Uganda.

Objective

Energy use in Uganda is characterized by long cooking hours and the practice of cultural cooking routines that households claim to be important for their subjective well-being. The assumption in this study is that these cooking routines are causing excessive energy use and the incumbent clean technologies (improved cookstoves) do not appear to address this challenge. No study has tried to investigate whether food preparation routines in Uganda lead to excessive energy use and whether the use of improved cookstoves could address the expected effect. To this end, we hypothesize that.

H1: *Food preparation routines with increased cooking time increases energy use and energy cost*

H2: *Use of improved cookstove technologies reduces the effect expected under Hypothesis 1.*

Data

Qualitative and quantitative survey data from three user segments including 169 households, 63 institutions (schools) and 59 restaurants collected from central Uganda was used to examine the energy efficiency associated with improved cookstoves under traditional cooking routine conditions. The data contained the amount of fuel used, the cost and the stove and fuel type used by the three user segments.

Analytical methods

The information collected from all three segments was used to calculate energy use per person meal and energy cost per person meal; these were our dependent variables of interest. To assess the effects of the user segment, food, fuel source and stove type, a linear mixed model was estimated with log energy use per person meal produced as the dependent variable. Food and user ID were specified as random factors. User segment, fuel source and stove type were specified as fixed factors. Due to incomplete crossing, all effects of stove type and fuel source (either charcoal or firewood; the altogether 14 users of other fuel types were excluded) had to be nested under the user segment. The model was estimated by restricted maximum likelihood (REML). The same model was estimated again with log energy cost as the dependent variable.

Research Findings

Compared across foods, the variation in energy efficiency was considerable. The least energy-efficient food preparation (beans, at an average energy cost of 70.34 UGX per person meal and average energy use of 4.00 MJ per person meal) required on average four times as much as the most energy-efficient food preparation (fish, at an average energy cost of 17.79 UGX per person meal and average energy use of 1.40 MJ per person meal). Hence, the results support H1. Compared across fuel source and stove type, we expected that improved cookstove technologies would mitigate excessive energy use. However, no such effect was found. Hence the results do not support H_2. The results from this paper show that the current generation of clean cooking technologies (improved cookstoves) does not appear to alleviate problems of excessive energy use: there were no usage contexts in which they differed significantly from traditional cooking technologies (3-stone). This result coupled with qualitative findings and observations from the survey revealed systems weakness in the incumbent clean cooking technologies that informed the objectives in the third paper.

Paper contribution

This paper analyses the energy efficiency of the incumbent clean biomass technologies using social-cultural considerations embedded in food preparation routines in Uganda. This analysis is important to understand as it could influence policy decisions on promoting or phasing out incumbent inefficient technologies to pave way for a cleaner, more efficient, and sustainable energy technologies. The results from this study can be used by transition actors like entrepreneurs and policymakers to implement niche projects in the bioenergy sector. Furthermore, the empirical findings can be used to update Uganda's policies related to disrupting the incumbent (improved cookstove) technological systems and create niche opportunities for investment into other renewable and sustainable energy technologies and resources in Uganda. The results can further influence policies related to preserving energy resources like forests and the ecosystem.

7.3. Paper 3: Realizing the transition to bioenergy: Integrating entrepreneurial business models into the biogas socio-technical system in Uganda.

Objective

Current and past research on the biogas socio-technical system has ignored the possibility of integrating entrepreneurial business models into the biogas socio-technical system to exploit its potential for wider social benefits. Relatedly, there is a lack of knowledge on how entrepreneurial models, could be practically effectuated especially in developing countries. This has left would-be entrepreneurs in developing countries thinking that biogas businesses are lacking commercial feasibility. To address these shortcomings and misunderstandings, this paper develops a model that shows how a commercial biogas supply chain could be pursued (effectuated) to realize a sustainable energy transition. The main objective of the paper is *to assess the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit.*

Data

This paper uses multiple data sources and mixed methods such as qualitative and observation data obtained from semi-structured (key informant) interviews which were part of the study survey used in Papers 1 and 2, data from document analysis and feasibility study. The Transitional Model Canvas (TMC) (van Rijnsoever & Leendertse, 2020) was the main analytical tool used to analyze and process the data. Data from the qualitative findings, observations and document analysis were used to create and inform the TMC for bioenergy in Uganda.

Analytical methods

The Transitional Model Canvas (TMC) was used as a practical tool to analyze the data obtained from different sources. The TMC provides a transition trajectory that involves analyzing the incumbent biogas system, the niche system, and the landscape structure. Data from the feasibility study was analyzed by comparing the local and international scenarios; the average marginal costs were compared.

Research Findings

Results from the qualitative interviews and observations indicate that households using biogas cook in cleaner and more dignified environments compared to their counterparts who use firewood and charcoal. The TMC model shows that bottling biogas and biogas entrepreneurship is missing in Uganda. Furthermore, the results of the feasibility study indicated that by sourcing materials locally, system builders (entrepreneurs) could achieve a marginal cost reduction of 64% compared to when they are imported. This implies that investing in upgrading and bottling biogas as a clean fuel is feasible and that the bioenergy transitions in Uganda could be realized through an entrepreneurial process.

Paper contribution

This paper makes some nascent contributions; first, the paper contributes to solving a real-world problem and builds on the literature on action research methods (Wittmayer et al., 2014). The TMC framework presents a practical solution that developing countries could explore in the energy transition process. Secondly, the paper builds on the works of other scholars that have discussed the role of university research in innovation and the use of scientific knowledge in society. Thirdly, the ideas presented here contribute to sustainable development goal 7 (UN General Assembly, 2015 7. a, 7. b). Increasing access to clean energy can improve the living standards and social well-being of households in developing countries, thus, addressing SDG 3. Energy and innovation actors in developing countries could use such knowledge to develop policy strategies concerning increasing access to clean energy in underserved communities.

7.4. Paper 4: Valorization of biogas for market development and remission of "environmental nuisances" in Uganda.

Objective

Biogas in Uganda is considered a pro-poor renewable energy source (Bluemling et al., 2013). consequently, its promotional value has been underestimated, yet, it has a high potential to enable individuals and households to live in a clean and sustainable society (Clemens et al., 2018; FAO, 2018). More to that, adding value to biogas can enable producers to obtain productive applications for biogas in ways that create tangible and monetary value for individuals, households, and the wider society. From this background, *the objective of this paper is to explore how biogas can be valorised to stand a chance as a commercial market offering and reduce "environmental nuisances" in Uganda.* The valorisation of biogas could enable its integration into the future sustainable energy supply systems in Uganda.

Data

To explore the objective of this study I used qualitative primary and secondary data. Primary data was obtained through case study analysis, pilot productions, observations, and stakeholder analysis surveys. Secondary data was obtained from SNV-The Netherlands development Agency promoting biogas technologies in Eastern Africa.

Analytical methods

Data from the pilot production was analysed and results were presented using X-bar/R control charts for input concentrations of methane (CH4), carbon dioxide (CO2), hydrogen sulphide (H2S) and oxygen (O2) at the pilot plant. Data from the customer interest survey was analysed using Correspondence Analysis (CA) in three dimensions and jointly hierarchically clustered, using Ward's method. The results from the CA dimensions were presented using biplots while the joint hierarchical clustering was presented using a dendrogram.

Research Findings

The results revealed that the biogas produced at NaLIRRI does not have the required quality (98% methane) to stand a chance as a commercial market offering; the pilot production process never even got close to the lower specification level of 95% for upgraded methane (CH_4) and the upper specification level of 5% for carbon dioxide (CO_2) in the upgraded gas.

The study also found that small-scale biogas producers have excess gas which they release into the atmosphere; with a high desire to sell it, but with no idea of how to valorize the gas to reach the market. These findings indicate that biogas production from small-scale producers can attract business development although this could be on a small scale, given the size of the farmers' digesters (mainly $13m^3$). Clear clustering of the product category, bioelectricity/biogas, revealed three promising customer segments: bioenergy entrepreneurs, gas companies and electricity suppliers.The results thus imply that to become a commercial market offering, the quality of biogas needs to be improved using technological and valorisation strategies like monitoring gas quality, shaping the market, market research and certification and controls.

Paper contribution

This paper empirically contributes to action-oriented mechanisms of generating demand for energy that is cleaner than energy from conventional sources. The findings also build on literature addressing limited access to clean, affordable and sustainable energy for all (MoEaMD, 2015; UN General Assembly, 2015 7.a, 7.b), reducing emissions and mitigating climate change (Mazorra et al., 2020). Furthermore, this article contributes ideas to the renewable energy policy, particularly on how to reduce the energy supply gap through valorization and integration of biogas into the renewable energy mix in Uganda.

In summary, the contributions of this thesis are at the intersection of research, innovation, and impact (Etzkowitz & Leydesdorff, 2000; Gulbrandsen & Smeby, 2005). Figure 3 summarizes the contributions of this research using a triple helix model. The model shows the contribution of this research at three levels: the state (policy), industry (entrepreneurship) and University (R&D). In Figure 3, the industry engages in the production of innovations (e.g., developing biogas upgrading systems) researched by university scholars, with the support of state subsidies (from the state actors). As the industry produces the technologies, and builds innovation systems and industries, they create employment opportunities and provide clean energy to the wider society. This helps to address landscape pressures like mitigating climate change. The state could provide funding to scholars for more R&D into bioenergy which creates more innovation options for the industry. More to that, the state can reduce taxes for such industries and benefit from reduced pressure on biomass resources through wider society's access to clean energy. The state resources for mitigating climate change can thus be saved when environmental conservation is achieved. overall, the biggest beneficiary of this research is the wider society which will have increased access to clean energy.

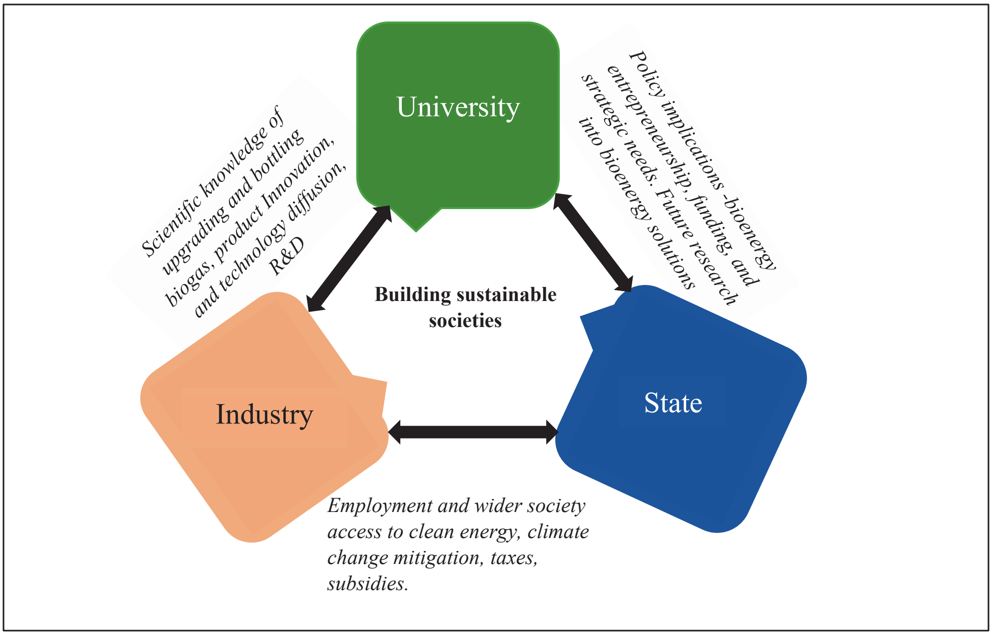

Figure 3: summary of research contributions in a Triple Helix

6. Policy recommendations and conclusions

Although households' traditions contribute to subjective well-being, they can also affect objective well-being which involves the destruction of the environment and climate change caused by unsustainable cooking cultures. To avoid cultural conflict with state regimes, governments of developing countries should develop stringent policies on biomass resource use while subsidizing biogas production to reduce the use of inefficient technologies like the traditional 3-stone and the improved cookstove technologies.

Uganda's energy policy should focus on enabling technological transitions through designing and implementing market development-directed policies for biogas systems. This could include investing in biogas valorisation technologies tailored to micro-level productions like the ones operated by small-scale farmers. This way, biogas could become mature enough to stand a chance as a commercial market offering.

Government policy should encourage biogas entrepreneurship through biogas containerisation for easy marketability and accessibility.

The state should shape sustainable biogas markets by constructing the narrative, proving the system, and encouraging exchange practices. Particularly, the state should press ahead with constant communication of the positive role of biogas in energy and agricultural sector improvement.

Governments should support waste recycling through innovative ways like sorting waste at the source and promoting large-scale private sector investment into biogas production to utilize the sorted waste.

National policies should support technical capacity building and training to meet the skills demand for a growing biogas market.

Significant investment in new biogas technologies and sector regulation through certification and controls in Uganda is needed to achieve large-scale and quality biogas production.

In conclusion, biogas resources in Uganda are enormous and have easy accessibility, they are not even affected by political tensions. There is also an existing infrastructure for natural gas in Uganda that biomethane producers could take advantage of to reach a large customer base. On the other hand, forest-based resources are depleting and the existing geo-political tensions around the world have induced energy instability and high fuel prices. The production and use of biogas and digestate mean inter alia, increased energy and food security, reduced dependency on chemical fertilizers, creation of local jobs, new business opportunities and increased knowledge base. Developing biogas energy markets and converting waste resources into energy and fertilizer would also provide a setting for industries to be brought into rural communities and potentially create jobs that will bring incomes into rural systems. If implemented, the market development options discussed in this thesis will allow biogas to play a key role in achieving a sustainable energy future for Uganda. A major takeaway from this research could be that, as sub-Saharan Africa recovers from the effects of the COVID-19 pandemic, adjoined with the effects of the geo-political war between Russia and Ukraine, that has caused skyrocketing energy and/or fuel prices around the world, and limited local access and affordability of necessity products, it would be important for governments of developing countries to consider promoting market (business) development solutions (policies) for bioenergy systems, as a driver for sustainable energy transitions.

7. Limitations and future research

The work in this thesis is empirical and aimed at studying market development solutions for a sustainable transition to clean energy in Uganda. The thesis's main objective was to investigate and elaborate on how developing countries like Uganda can scale appropriate technology transitions in the bioenergy sector. While exploring this research question, some limitations were encountered which are important to note. First, the study uses two different theories, sustainability transitions and business model innovation. The former suggests change while the latter enacts and/ or enables change. However, bringing out the flow of this discussion in an action-oriented way is not simple work. It requires a deeper understanding of both theories to generate the most important concepts and put them into perspective. This caused the researcher to read a lot of literature to understand how to merge the two theories to inform and contribute to the energy transition discussion. Second, research on bioenergy in Uganda is underdeveloped; there was no available data on the biogas resources available related to biogas production and supply to support studies of this nature. This caused the researcher to take much time developing instruments for different field studies. Third, upgrading biogas is still a novice in Uganda and has limited state focus and policy concentration despite its promising role of relieving Uganda's energy burden. This limited access to reference material on upgrading biogas in a developing country context. Finally, there is limited bioenergy engineering expertise and capability in terms of upgrading biogas to biomethane in Uganda. The current entrepreneurial activities in biogas stop at constructing biodigesters without valorising bio-products. This limited consultations on biogas systems during data collection.

For an expanding population living in a small country like Uganda, with limited access to clean energy, developing clean bioenergy systems is acute. However, the above limitations show that Uganda has a considerable catching up to do if their bioenergy systems should develop a "data ecology" comparable to that of the G7 countries. Therefore, future research should focus on addressing the above limitations. Particularly, future research should focus on building dynamic capabilities and productive supply chains necessary for bioenergy production, valorisation, and market development for successful sustainable energy transitions. Future research should also focus on designing and building technology-appropriate biogas upgrading technology tailored to micro-level digesters. This will help biogas producers to utilize the excess gas and link them to the wider market while reducing emissions from greenhouse gasses. Addressing clean energy challenges in Uganda will also require a focus on the directionality of socio-technical systems, and a more participatory and inclusive approach like the one studied in this thesis.

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RESEARCH PAPERS

Paper I

Do biomass technology innovations improve subjective well-being? Traditional versus Improved cookstoves in Uganda

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Highlights

- Improved cookstoves move households away from their intangible cultural cooking heritages.
- Households with no improved cookstoves cannot change from their traditional cooking practices.
- Producers need to consider households' subjective well-being when designing technologies.
- Policies on clean cooking should consider the preservation of cultural values.

Abstract

This study investigates the dark side of biomass technology innovations on households' subjective well-being in Uganda. The dark side of biomass technology innovations concerns households moving away from the intangible cultural cooking heritages they have preserved for a long time. These intangible cultural cooking heritages are important to understand as they contribute to policy decisions on sustainable society transformation (sustainability transitions) in the clean cooking energy sector. This study adds to the scarce literature on innovation for well-being and innovation for transformative change that includes addressing grand societal challenges while considering the well-being of technology users. Principle Component Analysis was used to generate the subjective well-being variable from the captured household traditional cooking considerations, perceptions, and practices. Linear regression was used to analyse the effect of improved cookstoves and other factors on the subjective well-being of households in Uganda. Results show that using ICS move Ugandan households away from traditional ways of cooking, which reduces the well-being they attach to the intangible cultural heritage of traditional cooking. Thus, innovators, entrepreneurs and promoters of clean cooking technologies should consider the well-being of users along with the benefits of bioenergy innovation to accelerate society transformation (sustainability transitions) in Uganda.

Keywords: Dark side of innovation, subjective well-being, innovation for well-being, improved cookstoves, intangible cultural cooking heritages, Sustainability transitions

1. Introduction

Research on Improved biomass technologies has positioned these technologies as the main socio-technical strategy for reducing emissions caused by indoor air pollution, that are associated with household use of solid biomass in developing countries (Catalán-Vázquez et al., 2018; Lindgren, 2020). Consequently, providing access to improved biomass technologies continues to be a priority for development actors like the United Nations (UN General Assembly, 2015; Zhang, 2022). Since the inception of these technologies in developing countries in the 1950s, several studies have been undertaken to understand their association with user uptake in society. For example, Jan and Lohano (2020) found that the uptake of improved biomass technologies is significantly associated with high education and income levels and that the technologies reduced indoor air pollution, which improved the health of households. Misra (2012) and Kishore and Ramana (2002) found that improved cookstoves (ICS) reduce biomass usage, which contributes to nature conservation and environmental sustainability. Ray et al. (2016) and Rwiza (2009) found that using ICS improves economic growth which contributes to the creation of social and economic well-being by reducing cooking and firewood gathering time and good health to households.

Whilst previous studies explore several factors and contributions of biomass cooking technologies on society, it could be argued that they have ignored the empirical analysis and documentation of the dark side of improved cookstove technologies on household's subjective well-being (Engelbrecht, 2018; Spanakis et al., 2016). Martin (2016) and Spanakis et al. (2016) assert that the possibility of innovations having a dark side on household subjective well-being cannot be ruled out. This may concern intra-personal subjective well-being related to health beliefs, knowledge, attitudes or values, and inter-personal well-being among individuals and in societies. The dark side of ICS could be related to the changes in household subjective well-being as the households move away from traditional to improved cooking practices. Traditional cooking practices are intangible cultural cooking heritages that households have practised and preserved for a long time (Wirth et al., 2013). These practices are passed on from one generation to another with a symbolic meaning and special significance that has origins in the past. Any threat to erode such traditions threatens the households' subjective well-being of using and preserving them (Lang & Caraher, 2001).

In Uganda, traditional cooking practices were associated with cultural values like cooking with open fires keeps our traditions alive, and we are strong because of the way we cook our millet bread (Amone, 2014). While cooking and gathering around the open fire, parents told stories and riddles to children that carried the knowledge concerning acceptable behaviour in society and responsible living (Kweyunga, 2013). Although changing from traditional to improved cooking practices reveals positive societal and environmental impacts (Lindgren, 2020; Singh et al., 2012), moving away from intangible cultural heritages associated with traditional cooking practices can be considered a dark side of clean cooking technologies. In a review paper, Lindgren (2020) found that studies on technology adoption in Asia and Sub-Saharan Africa have not accounted for the cultural and social needs of users, such as recognizing that cooking practices often serve specific traditional purposes for communities and families. In Ugandan societies, cooking traditional foods on an open fire has a symbolic connection to a strong cultural heritage that represents specific norms, beliefs, and values related to different foods. Qualitative (anecdotal) findings of this research indicate that Ugandan households, consider food cooked on open fires to have a unique, natural taste and distinct aroma caused by the smoke that perforates into the food during cooking. This attribute is considered absent in food prepared over-improved cookstove technologies. However, no empirical study has been assessed to support or explore the validity of such evidence which this study does.

According to Bielecki and Wingenbach (2014) traditions are nested under three interlinked domains on which the dark side of ICS may be assessed. These include the social, cultural, and functional domains. The social domain relates to family size and meal occasions which concerns cooking for large family gatherings and big occasions of which ICS may not serve this purpose. The cultural domain concerns the local norms, customs, traditions and views on aesthetics and well-being that are likely to be affected when using ICS technologies. The functional domain concerns the ability to provide space, heat, and ambient light. For instance, improved cookstoves have no burning flames that could enable households to sit around the fire, especially at night. Besides, elders often passed on discipline, told stories, and talked to their children about life at cooking time, as flames of fire provided warmth and light (Kweyunga, 2013). These domains and values of traditional cooking are associated with food satisfaction and social well-being, which can be eroded by ICS innovations. Therefore, understanding the dark side of innovation is important for a comprehensive evaluation of people's subjective well-being beyond the common assessment of the bright side of innovation. In this regard, the purpose of this study is to investigate whether improved biomass technologies (improved cookstoves) have a dark side on households' subjective well-being of practising traditional cooking methods. To investigate this dark side, we hypothesize that,

H_o: Using improved cookstoves reduces the household's subjective well-being of practising traditional cooking methods.

This investigation is important for informing producers, promoters, and policymakers of clean technologies about the importance of considering society's values and traditions when addressing societal challenges as this can accelerate sustainability transformations.

Kweyunga (2013) found that in central Uganda, cooking traditions relating to Uganda's signature cuisine "*matooke*" (plantain) are highly valued and practised. In this region *"matooke"* defines food. This food is thus prepared in a special way that requires high precision and careful handling relating to traditions. Additionally, traditional cooking is one of the main values taught to girls in Ugandan homesteads and is treated as a prerequisite to marriage. Marriage in Buganda (central region) is locally known as '*obufumbo*', which comes from an act of cooking (*okufumba*). Therefore, the values of traditional cooking in Uganda are rooted in culture and are valued as a cultural and national heritage that affects subjective well-being. Away from Uganda, Loo et al. (2016) found that majority of the women in western Kenya turned to use the traditional 3-stone technologies when cooking traditional dishes like "*nyoya*" with a view that it turns out well when cooked traditionally. Lang and Caraher (2001) found that traditional cooking has a place in people's everyday life, and cooking heritage contributes to national pride. Lang and Caraher also report that in Scotland and Northern Ireland, traditional cooking was retained on the curriculum as a symbol of national pride that must be passed on to young generations.

Consideration of cultural heritages in technological innovation is thus part of the paradigm shift from innovation for wealth creation to innovation for transformative change which accounts for households' subjective well-being (Diercks et al., 2019; Schot & Steinmueller, 2018). This implores policy to look beyond improving only the economic well-being of using clean technology and consider other intangible well-being factors that might delay sustainability transitions like cultural cooking heritages. The concept of innovation for well-being has in this case emerged as a central notion in science, technology, and innovation research (Castellacci & Tveito, 2018; Martin, 2016). This research contributes to such knowledge by comprehensively exploring the specific cultural attributes that the use of ICS technologies might cause households to move away from. Furthermore, this can inform innovators, entrepreneurs, and policymakers to develop technologies that are inclusive of economic social and cultural factors. The rest of the paper is structured as follows. Section 2 discusses the theoretical framework concepts used in framing the study. Section 3 explains the methodology used in the study. Section 4 presents the results, discussions and limitations of the study and Section 5 provides conclusions and recommendations.

2. Theoretical framework

Developing countries continue to promote clean energy technologies through innovation policies to improve the well-being of households (Schot & Steinmueller, 2018). However, it can be argued that many of the societal challenges facing the world today are caused by both the direct and indirect effects of innovations Diercks et al. (2019). A new paradigm has thus emerged arguing for innovative research and policy to focus on addressing broader societal challenges like resource depletion, climate change, cultural dynamics, and demographic change (Schot & Steinmueller, 2018). This implies that clean innovations influence all societal domains and to create societal transformation, innovation policy needs to promote all societal goals and values, including cultural heritage preservation. This paradigm thus considers innovation for society's and/or subjective well-being which is rarely discussed in the literature (Tura et al., 2019).

Subjective well-being (SWB) corresponds to individuals’ perceptions of what makes a good life (Castellacci & Tveito, 2018; Dolan & Metcalfe, 2012b). Subjective well-being includes aspects like, cognitive evaluations of one’s life, happiness, life satisfaction, positive emotions such as joy and pride, and negative emotions like pain and worry (Diener, 2009). With SWB, Kahneman and Krueger (2006) denote that people idiosyncratically develop perceptions that enable them to think of life from lived experiences. Individuals have different subjective perceptions which they base on to evaluate their past and current life concerning the conditions in which they live (Diener, 2009; Diener et al., 1985). This evaluation of one’s life allows people to determine whether they are living a good, satisfied, or dissatisfied life. Kahneman and Krueger (2006) found that SWB is measured based on a bottom-up approach to life satisfaction where a combination of life-lived experiences informs people’s reported feelings of happiness or unhappiness. Fujiwara et al. (2014)

state that to comprehensively understand the effects of innovations on subjective well-being, several variables should be considered and measured separately in surveys. Diener et al. (1985) and Pavot and Diener (2008) have used the satisfaction with life scale (SWLS) to extensively assess and measure different domains of life on SWB. This tool includes measures like economic value, happiness, satisfaction with life, culture, pride, pain, and worry (Spanakis et al., 2016). These measures have, however, not been applied in assessing individual use of innovations, particularly cooking technologies.

2.1 Measuring subjective well-being (SWB)

Although the construct of subjective well-being is complex to conceptualize, operationalize and measure (Dolan et al., 2008), Diener's satisfaction-with-life scale proposes a cognitive measure that uses individual self-reported measures to assess the quality of life. Dolan and White (2007), Krueger and Schkade (2008) and Martin (2016) found that self-reported subjective well-being is considered the best estimate of overall utility, thus it is well applicable for evaluating subjective well-being concerning the use of technologies. Kahneman and Krueger (2006) assert that self-reported subjective well-being encompasses a cocktail of life domains, that are closest to people's personal lives and can influence their subjective well-being. However, according to Diener (2009) and Sagiv and Schwartz (2000) self-report is not the only way to measure subjective well-being, other specific components of subjective well-being exist although, the decision of which measures to use depends on the goals of a particular study. In this regard, Castellacci and Tveito (2018) assert that exploring the potential bright and dark side effects of innovations on subjective well-being requires assessing the economic and social value creation and destruction of technologies.

The economic value creation concerns preference satisfaction and how policies can be crafted concerning subjective well-being. The economic view further contends that individuals work as much to earn an income from economic activities, as to spend on the consumption of items that fulfil their basic needs, which allows them to live a socially competitive and satisfying life (Dolan et al., 2008). Income influences household decisions on technology use and technology can improve the subjective well-being of individuals (Castellacci & Tveito, 2018; Chesley, 2005). However, Diener and Seligman (2004) and Diener (2013) report that the economic view does not fully account for subjective well-being since economic growth may not certainly create higher subjective well-being, and people may be unhappy even with rising incomes. Therefore, there are other indicators like social capital and a clean and healthy environment in societies that could explain well-being beyond economics. These indicators are related to perceptions of lived experiences, and not utility as economists state. Krueger and Stone (2014) found that perceptions are a more exact measure of how people feel especially if they are reported in real-time or recall the experience.

Perceptions are defined by the social construct, and they help to evaluate explicit domains and activities like cooking, working life and health, they also involve an assessment of one's social status or societal living standards (Castellacci & Tveito, 2018; Krueger & Stone, 2014). These social domains are explained by the physical and environmental factors such as location, health, and existing social regimes (trust, governance, crime, social amenities, social and national artefacts, religion, values, politics, cultural heritages, time, education, motivations, age, gender, technology, and self-status). A combination of these factors can negatively or positively influence one's subjective well-being (Castellacci & Tveito, 2018; Spanakis et al., 2016).

For instance, realizing and respecting one's traditional values, and acceptance of people's customs and beliefs that traditional culture offers may be fulfilling, life satisfying and associated with individual well-being (Diener et al., 1999; Krueger & Schkade, 2008; Sagiv & Schwartz, 2000). Diener et al. (1999) further found that people are happier if they have attributes that are consistent with cultural norms, beliefs, and values because cultures hold traditions that inspire what people consider to be most important to their social well-being. Nevertheless, the social construct follows Bielecki and Wingenbach (2014) social, cultural and functional domains as discussed above. Therefore, from the cultural dimension, we empirically investigate whether improved cookstoves have a dark side of moving households away from the intangible cultural heritage preservations using the methods outlined in the next section.

3. Materials and methods

3.1. Sampling and data collection survey

Innovation for well-being can be measured either on the whole population or a specific group of people using longitudinal or cross-sectional survey data (Dolan & Metcalfe, 2012a;

Engelbrecht, 2018). Using cross-sectional survey data collected between July - October 2019, we investigate the dark side of improved cookstove technologies on the subjective well-being of households in central Uganda. Uganda is a country in Sub-Saharan Africa, particularly in the Eastern Africa region. The country is divided into four regions: Central, Eastern, Northern and Western as shown in Figure 1. The four regions are further subdivided into a total of 134 districts. From the 134 districts, we sampled four districts in the central region namely Kampala, Wakiso, Mukono and Luweero. The sampled districts are marked with a red star in Figure 1. These districts were selected because they have a higher adoption rate of improved cookstove technologies (UBOS, 2014, 2021). Considering the inequality gap that influences the decision of a household on whether to have an improved cookstove or not, data was collected from both rural and urban areas. Out of the four districts, Kampala and Wakiso data was from the urban areas while in Luweero and Mukono districts the data was collected from the remote or rural areas away from the urban centers.

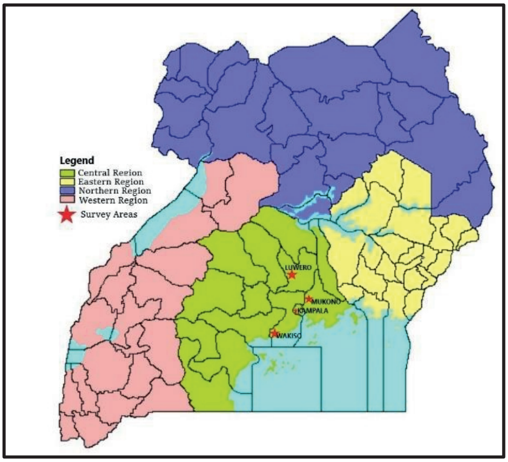

***Figure 1**: Survey areas in central Uganda*

Before the data collection, we developed a survey instrument to capture data on household cooking perceptions, considerations, and practices of using improved cookstoves vs Traditional Cooking Methods (TCM) with related questions on traditional cooking heritages and subjective well-being. The data was collected using computer-assisted personal face-to-face interviews (CAPI). After a thorough review of the data instrument, we transformed it into a digital format using the Open Data Kit (ODK) that is installed on android tablets. Our unit of analysis was the household. We targeted the decision makers (household heads), the person(s) with the main responsibility for purchasing and using cooking technology. However, some households used both improved and traditional cookstoves but were categorized among those using improved cookstoves.

Borrowing from the dominant satisfaction-with-life scale (Diener et al., 1985; Krueger & Schkade, 2008) we developed a set of perceptions to measure and understand the effect of ICS innovations, compared to traditional cook stove (TCS) technologies, on household subjective well-being in central Uganda. We anchored the perceptions on a 7-point Likert scale with 1 =strongly disagree, 2=disagree, 3=slightly disagree, 4=neither agree nor disagree, 5=slightly agree, 6 =agree, and 7 =strongly agree.

3.2. Analytical model

To measure the subjective well-being of households, we used nine (9) Likert scale questions (following the Likert measures specified in section 3.1). The questions were related to traditional cooking considerations, practices, and perceptions. Out of the nine (9) Likert scale questions, we obtained a linear variable that combined all the responses using Principal Component Analysis (PCA) (Kurita, 2019). This is because subjective well-being is a latent variable, and several variables can define well-being. The goal of using the PCA was to identify the most meaningful basis to re-express and reveal the hidden structure of the nine questions. The stated questions were; 1) Cooking with open fires keeps my tradition alive, 2) I like my food cooked with open fire, 3) I eat from home (here) because the food has a distinct aroma, 4) Food cooked on an open fire has a distinct taste, 5) The way I cook is very important for my tradition, 6) I have more confidence when cooking traditional foods on an open fire, 7) A traditionally cooked meal gives me a sense of security, 8) I feel proud when eating food cooked on an open fire, and 9) To me, cooking on improved stoves connects with happiness and a feeling of well-being". The PCA weights of these questions are presented in Table 3 Appendix I. In determining the score for the Subjective well-being of households, the three questions with higher eigenvalues were (1) cooking with an open fire keeps our traditions alive, (2) I like my food cooked with an open fire, and (3) I eat from home (here) because the food has a distinct aroma.

Using the SWB score generated from the PCA as the dependent variable, we tested H_o using a linear regression model. We express the linear regression model as.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \mathcal{E}_i \text{ .... } (1)$$

Where:

The dependent variable Y, is the SWB score as a continuous variable generated from a Principal Component Analysis (PCA). The independent variables are gender (1=female), Education

(1=above primary), Health (1=long life is important), Fuel used (1= Firewood & charcoal), Do not have ICS (1=yes), ICS advantages (1=cost saving), Household size, Monthly Income (Ugandan Shillings[1]), change cooking practices (1=yes), confidence with open-fire cooking (1=yes)

4. Results and discussion

4.1 Descriptive Statistics

Table 1 presents the descriptive statistics of the variables used in the model. The sampled households were 169, spread across the four districts marked in Figure 1. From the sampled households, education was captured as binary, one (1) representing household heads who have attained at least primary education and zero otherwise. From Table 1 approximately 70% had attained at least primary education. We also observed the gender of the household head where our sample represented 72% being males in an average household size of 5 members. From the economic domain, we captured household monthly income. On average, the households reported having a monthly income of 469553.6Ugx. We captured the health variable as binary, one (1) indicating having a long life is important and zero (0) otherwise. The question on the health domain was "To me, a long life and being in good health are important factors, so I carefully consider the technology I use to cook". On average, about 65% of the sampled households perceived it important to have a long life. Regarding cooking fuel, a larger sample (93%) of the households reported using firewood and charcoal as the main fuel leaving the smallest sample to other fuel sources like electricity, biogas, Liquified Petroleum Gas (LPG) and kerosene. For households using improved cookstoves, the main advantage reported was cost saving. The dependent variable SWB, captured as a continuous variable, has an average score of 3.45 with a standard deviation of 1.74. A detailed description of the variables used in the model is presented in Table 1

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[1] At the time of the study, 1Ugx= 0.00027064 USD

Table 1: *Description of independent and dependent variables used in the model to explain and measure subjective well-being of practicing traditional cooking in Uganda*

Variable	**Frequency**	**Percentage**	**Definition**
Education (1= above primary)	115	69.70	The education level of the household Head (Dummy 0= below primary and 1= Above primary)
Health (1=long life is important)	110	65.09	The healthy cooking technology is important =1; 0 = otherwise. Dummy variable constructed from the question: "To me, a long life and being in good health are important factors, so I carefully consider the technology I use to cook"; Likert scale (1-7)1=completely disagree and 7=completely agree; where 5-7 is defined as 1= Important and 1-4 is 0= Not important.
Gender (1=Female)	47	28.14	Gender of household head (0 =Male and 1= female)
Fuel used (1= Firewood & charcoal)	158	93.49	The main fuel used to cook in a household (dummy variable,0=LPG gas, Electricity and Kerosene, and 1=firewood & charcoal
Do not have ICS (1=yes)	55	32.54	Dummy:1=Household without ICS, 0= Household with ICS
ICS advantages (1=cost saving)	124	73.37	Dummy: 1= cost saving, 0= Time saving
Change cooking practice (1=yes)	120	71.01	Perception, "We can change our cooking practices from traditional technologies to Improved ones" Likert scale variable (1-7; 1=completely disagree and 7=completely agree) converted to Dummy <=4= Completely disagree and >4= completely agree)
Confidence with open-fire cooking (1=yes)	85	50.30	Dummy variable generated from perception "I have more confidence when cooking traditional foods on an open fire" Likert (1-7) 1=completely disagree and 7=completely agree (Dummy, 1-4=0 "disagree" and 5-7=1 "Agree"
Variable	**Mean**	**St. dev**	**Definition**
Household size	5.28	3.38	Number of people that live and eat in the household (including the respondent)
Monthly Income (UGX)	469553.6	712134.7	Average household monthly income; in millions of Uganda shillings (UGX), I UGX = 0.00027 US $. The maximum income was 5 million UGX
Well-being (SWB score)	3.46	1.74	Principal component variable generated using Principal Component Analysis (PCA)

4.2. Regression results

Table 2 shows the results from the regression model. The overall model is significant at 5% with 38% of the independent variables explaining household subjective well-being of traditional cooking methods.

Table 2: Linear regression analysis

Y=Well being	Coefficient	P-Value
Do not Have ICS (1=Yes)	0.297* (0.157)	0.061
Education (Category)	-0.125 (0.155)	0.42
Health	-0.099 (0.146)	0.5
Household size	-0.016 (0.018)	0.367
Average monthly income (log)	-0.156 (0.095)	0.102
Gender (1=Female)	0.049 (0.147)	0.74
Fuel (1=Firewood)	-0.093 (0.223)	0.678
Open fire saves cooking time	0.18*** (0.033)	0.00
ICS saves Fuel (1=yes)	-0.278* (0.144)	0.056
Change cooking practice (1=yes)	-0.318** (0.146)	0.031
Confidence with open-fire cooking (1=yes)	0.153 (0.129)	0.238
Number of obs = 163 F (11, 152) = 8.51 Prob > F = 0.0000 R-squared = 0.3810		

Notes: Standard errors in parentheses **** p<0.001, *** p<0.01, ** p<0.05, * p<0.1 denotes significance at the 1,5 and 10 % level respectively

In the model, variables that statistically explain the change in well-being are (1) do not Have ICS, (2) open fire saves cooking time, (3) ICS saves Fuel, and (4) change cooking practices. We note a significant positive effect on the households reported not having ICS on subjective well-being at a 10% significant level. Not having ICS increases the subjective well-being of households by 29.7 percentage points, ceteris paribus. We observed the same positive significant effect on the households who reported that open fire saves their cooking time at a 1% significant level. This implies that open fires saving cooking time contribute to subjective well-being by 18 percentage points. We further observed a negative effect of improved cookstoves saving fuel and changing cooking practices on subjective well-being. Households who reported that ICS saves cooking fuel and can change cooking practices from traditional to improved ones, their subjective well-being reduced by 28 and 32 percentage points respectively. In the analysis, we controlled for education, healthy cooking technology, household size, gender, and income. We considered these variables to be key in determining the household cooking technology choice, and hence important control variables for assessing whether improved cookstoves have a dark side on the subjective well-being of households in Uganda.

4.3. Discussion

In H_o, we test whether using improved cookstoves reduces households' subjective well-being by practising traditional cooking methods. Our key indicator for assessing the subjective well-being of using traditional cooking practices analysis was the change of cooking practices from traditional to improved ones. We find a strong and negatively significant association between the change in cooking practices and the subjective well-being of traditional cooking methods. This implies that changing from traditional to improved cooking practices reduces the SWB of traditional methods related to cultural cooking values and that households in Uganda are less likely to change from such cooking practices. The findings from our study relate to the finding of Loo et al. (2016) and Lang and Caraher (2001) where households stuck to using traditional methods with a claim the improved cookstoves would not allow them to practice cultural cooking which affected their well-being. Based on these findings we cannot reject $H_{o,}$ and we conclude that using ICS has a dark side of moving households away from the intangible cultural cooking heritages they have preserved for a long time in Uganda. Therefore, households who do not have ICS cannot change their cooking practices from traditional to improved ones.

Furthermore, Bielecki and Wingenbach (2014) indicate that ICS has limited cultural and social attributes. They cook for a small number of households with an average of six (6) family members. The stoves are not able to meet the cooking demands of large family gatherings and occasions which denies households enough family time to socialise. From our qualitative findings, the household indicated that ICS do not have direct smoke perforating into the food which denies the food a good aroma and natural test. Households also indicated that many ICS use charcoal which does not produce smoke. The ICS that uses firewood are expensive to construct and for this reason, they used firewood on an open fire. Using firewood on an open fire enabled women to confidently practice their traditional cooking and helped them to serve their husband's tasty meals. The tradition of serving tasty meals to husbands was also discovered in rural Mexico as one of the reasons women turned to use traditional stoves and declined the use of ICS (Catalán-Vázquez et al., 2018). Aside from moving households away from their intangible cultural cooking heritages, our qualitative findings revealed that ICS cannot accommodate big pots and cannot cook for extended families. This finding was also revealed in the works of Bielecki and Wingenbach (2014). ICS were also indicated to be slow-cooking stoves compared to the 3-stone open fire that starts cooking right away when the fire is made. Additionally, the ICS stove has a strong ceramic liner that takes time to heat up and the fire needs to first spread on all the charcoal for the stove to start cooking.

However, transition actors may find our result a challenge for sustainability transition to cleaner energy sources. Many scholars have found that open fires have significant negative healthy, climate and environmental effects resulting from indoor air pollution and emissions (Catalán-Vázquez et al., 2018; Singh et al., 2012). Recommendations to overcome these negative effects of open-fire cooking have in the past been to switch to the use of improved cookstoves to save lives, the environment, and the ecosystem (Loo et al., 2016; Urmee & Gyamfi, 2014). Contrary to this recommendation, Kishore and Ramana (2002) and Nepal et al. (2011) found that the improved cookstoves are also not energy and cost-efficient which causes continuous resource depletion and environmental damage. The later authors thus recommend moving away from ICS to cleaner and energy-efficient technologies like liquid bioenergy. IRENA (2017), Clemens et al. (2018) and (Zhang, 2022) support the transition from ICS as clean technology to biogas as a better alternative to clean cooking. Therefore, although we cannot reject the null hypothesis in this study, we agree with the previous scholars that have recommended a transition to cleaner and sustainable energy sources like biogas. However, as sustainability actors consider moving away from improved cookstoves and other technologies that are not clean they should also consider incorporating cultural characteristics in the technologies they introduce to society. The findings and discussions in this study should thus inform policy actors and clean technology producers on the direction of regimes. For instance, the regimes should be fairer to the cleaner energy sources and unfair to the open fire and improved cooking technologies. This way regimes will not directly attack the intangible cultural cooking heritages but will improve cleaner energy developments and this may attract users of traditional technologies to move away from the wasteful energy sources while still practicing their cooking cultures.

4.3 Limitations and future research

Although this study makes promising contributions, it also has some limitations that cannot be ignored. First, the literature on innovation for well-being particularly concerning intangible cultural heritages is very limited. Second, the theory applied in this study uses literature from divergent disciplines including psychology, economics, innovation, and sustainability studies, thus caution should be taken when applying the results within one discipline. Third, the study has assessed the dark side of biomass innovations but does not show how this could increase or limit the uptake of improved biomass technologies for sustainability transitions. Thus, future research assessing the effects of biomass technologies on subjective well-being should seek to address these limitations. Particularly, the use of a larger sample and/or longitudinal survey could help to study the phenomena widely for better policy conclusions. Additionally, more research on user preferences for clean cooking and preserving the intangible cultural heritage of traditional cooking is needed for clean innovations to maximize subjective well-being and social welfare. This could accelerate a sustainable transition to clean energy in developing countries. Finally, future studies could also explore how the dark side of biomass technologies could inhibit sustainability transitions and sustainable development in Uganda and how regimes could embrace this challenge.

5. Conclusions and Recommendations

The study contributes to research on innovation for well-being. The article uses household survey data to explore the dark side of improved cookstoves on the subjective well-being of users, a concept that has been ignored by many clean cooking scholars. We find that using improved cookstove innovations is likely to have a dark side on households' subjective well-being in a way that improved cookstoves move households away from their intangible cultural cooking heritages (social, cultural, and functional traditions). This dark side of moving away from traditions implies that households could drop their traditional ways of cooking that form an important sense of belonging and cultural heritage they have preserved for a long time. Therefore, innovators, entrepreneurs and policymakers need to avoid the dark side of clean cooking innovations that affect households' subjective well-being. However, this dark side should not stop the actors from promoting cleaner energy sources as they will help to reduce the wasteful use of biomass and improve the health of users in Uganda. Households could thus be oriented on how to continue practising their important traditional cooking methods in food preparation but with cleaner energy resources and this will accelerate the transition to clean energy in Uganda.

Acknowledgements

I would like to thank the NORAD/NOHED project for funding this work.

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Appendix I

Table 3: Principal Component Analysis (PCA)

Variable	**Eigenvalue**
Cooking with open fires keeps our traditions alive	2.99478
I like my food cooked with an open fire	1.71469
I eat from home (here) because the food has a distinct aroma,	1.43806
Food cooked with open fire has a distinct test	.841656
The way I cook is very important for my tradition	.771906
I have more confidence when cooking traditional foods on an open fire	.602339
A traditionally cooked meal gives me a sense of security	.489795
I feel proud when eating food cooked on an open fire	.146773
To me, cooking on improved stoves connects with happiness and a feeling of wellbeing	0

Paper II

Unsustainable cooking culture: the effect of food preparation routines and improved cookstoves on biomass energy use in Uganda

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Highlights

- Uganda's cooking routines cause excessive energy use
- Improved cookstoves do not appear to alleviate problems of excessive energy use in Uganda.
- Clean energy regimes and niche actors should consider phasing out improved cookstoves.
- Regimes should focus on promoting alternative clean and efficient energy resources like biogas.

Abstract

This study investigates the effect of food preparation routines and improved cookstoves on biomass energy use in Uganda. Our findings reveal that food preparation routines with increased cooking time led to excessive energy use in Uganda. The findings further indicate that improved cookstoves do not appear to alleviate such problems of excessive energy use: there were no usage contexts in which improved cookstoves differed significantly from traditional cooking technologies. Previous research has neglected the effect of food preparation routines on energy use when analysing the energy efficiency of the incumbent clean cooking technologies. Therefore, using cross-sectional survey data, this paper provides a comprehensive analysis of Uganda's cooking culture (cooking routines) to show how it causes excessive energy use that leads to resource depletion. Improved cookstoves not being energy efficient is a major systems weakness of the incumbent clean cooking sector. Regimes and niche actors should consider destabilizing the incumbent system by building niches in alternative cleaner energy spaces like biogas. This will lead to a reduction in resource depletion, and environmental conservation and reduce climate change in Uganda.

Keywords: Keywords: Excessive energy use and cost; Food preparation routines; energy use and cost efficiency; cooking time; Incumbent Improved cookstoves; Uganda

1. Introduction

Reducing biomass energy use is a key energy policy target for developing countries (Lindgren, 2020). This is because the biomass resources in these countries have continued to deplete as they are used on mature, inefficient and unsustainable technologies (Namugenyi, Coenen, & Scholderer, 2022; UNDP, 2020). Zhang (2022) contends that the speed and scale of sustainable and efficient energy use in developing countries need to accelerate because less than 10 years are remaining to achieve Sustainable Development Goal 7: universal access to affordable, dependable, and modern energy services. The current levels of innovation and investment in energy-efficient technologies are, however, insufficient to reach the 2.4 billion people who currently lack access to clean cooking solutions in the developing world. In the case of Uganda, Kweyunga (2013) and WHO (2006) found that more than 95% of the population cooks with solid biomass (firewood and charcoal) on wasteful technologies in enclosed kitchens. The introduction of improved cookstove innovations was expected to address such wasteful energy practices as well as provide a clean cooking solution to the traditional and unhealthy cooking technologies in Uganda (MoEaMD, 2002). However, there has been no observed significant reduction in biomass use since the introduction of these technologies (UBOS, 2015, 2021). Similarly, Zhang (2022) found that the current innovations in clean cooking do not seem to have the required efficiency to meet the clean energy demands of people who lack access to clean cooking solutions. It is thus important to exponentially increase efforts to address this fundamental development challenge and put the ecosystem on track to reduce biomass use as well as increase access to clean energy in the fastest, most equitable way possible. This, increasing desire to reduce biomass energy use together with an argent need to accelerate access to clean energy, represents an ideal setting in which to analyse the energy efficiency of the incumbent clean cooking technologies in Uganda.

Energy use in Uganda is characterised by long cooking hours and the practice of cultural cooking routines that households claim to be important for their subjective well-being. The assumption in this study is that these cooking routines might be causing excessive energy use and the incumbent clean technologies (improved cookstoves) do not seem to address this challenge. No study has tried to investigate whether food preparation routines in Uganda lead to excessive energy use and whether the use of improved cookstoves could address the expected effect. To this end, we ask "do food preparation routines lead to excessive energy use in Uganda? Do the incumbent improved cookstoves help to reduce the negative effect of food preparation routines on energy use? In response to these questions, we hypothesize that

H1: *Food preparation routines with increased cooking time increases energy use and energy cost*

H2: *Use of improved cookstove technologies reduces the effect expected under Hypothesis 1.*

Food preparation routines in Uganda are embedded in the cultural cooking practices of the different ethnical groupings. Uganda has close to 56 tribes distributed within four different regions and endowed with a variety of foods that are prepared differently. Food varieties like "*matooke*", which is also Uganda's signature cuisine, are a staple for the central region. Traditionally, "*matooke*" is served warm and soft, it is therefore supposed to be kept on burning fire until it is all served out. This food is prepared with high precision (see Appendix II) following specific considerations. Some of the important considerations relating to food preparation gathered in this study include, "food cooked with open fire has a distinct aroma and taste because it is perforated by smoke", "cooking with open fires keeps our traditions alive because we can educate our children around the fire", and "a traditionally cooked meal is a source of my wellbeing". Similarly, Amone (2014) found that in Northern Uganda there was a strong attachment to the way of cooking millet bread (Kalo) because it was a source of their strength. Therefore, food preparation in Uganda carries different intangible cultural heritages with symbolic representations and cooking considerations that require different cooking methods and time.

However, with a growing population, that demands more land for agriculture and settlement, the resources to sustain such cooking routines have increasingly become scarce making such cooking practices unsustainable and needing a transition to other sustainable fuels (Namugenyi et al., 2022). According to Turnheim and Sovacool (2020), as global energy systems undergo a shift from conventional fuels to clean and renewable power production like bioenergy, solar and wind technologies, it is important to investigate the energy efficiency of incumbent technologies to create a case that will help to phase-out unsustainable technologies from society. Analysing the energy use efficiency of the incumbent clean cooking technologies in Uganda is part of this global movement. Such analysis could provoke the creation and development of innovations in sustainable energy technologies and the destruction of incumbent regimes that support the use of mature, inefficient, and unsustainable technologies.

Coenen and Díaz López (2010) assert that clean technology drives economic competitiveness and secures sustainability of the different sectors of the economy. Innovation into cleaner technologies and methods is thus acknowledged for increasing the knowledge base and causing technological, organisational, and institutional transformation of the existing social-technical systems. Although improved cookstoves are cleaner technologies compared to the open fire (3-stone) options, their current performance seems insufficient to achieve the necessary sustainability transition in Uganda's energy system (Clemens, Bailis, Nyambane, & Ndung'u, 2018). However, the energy efficiency of improved cookstoves has been investigated before by several scholars using overall thermal combustion and heat transfer to the cooking pot (Jetter et al., 2012; Venkataraman, Sagar, Habib, Lam, & Smith, 2010), laboratory experiments (Kees & Feldmann, 2011) and fuelwood consumption, (Johnson et al., 2013) indicators. The findings from these scholars show that the stoves were energy efficient and that they significantly reduce energy use. Contrary to these scholars, an analysis of stove type and firewood indicators, by Nepal, Nepal, and Grimsrud (2011) and Kishore and Ramana (2002) revealed that improved cookstoves did not help reduce biomass energy use and cost. Nevertheless, there is an increasing realization that reducing energy use is highly dependent on several complex factors such as socio-cultural aspects that determine final energy consumption patterns and these may hinder the performance of energy efficient technologies (Kivimaa & Kern, 2016). IEA, IRENA, UNSD, WB, and WHO (2021) posit that current endeavours to implement energy efficiency policies are not appropriately dealing with social and cultural aspects of energy use, thereby limiting their potential for initiating long-term energy transitions.

Therefore, this article without neglecting the importance of other inquiries focuses mainly on analyzing the energy efficiency of the incumbent clean biomass technologies using social-cultural considerations embedded in food preparation routines in Uganda. In the analysis, the article draws on insights from the transition theory to understand the continued existence of mature technologies. This understanding is important to determine whether these incumbent clean cooking technologies can be maintained or phased out of society to create a way for a cleaner, more efficient, and sustainable energy technologies. This can be used to drive sustainability transitions in the bioenergy sector. This analytical framework will thus be used to empirically contribute to Uganda's policies related to disrupting the incumbent (improved cookstove) technological systems and create niche opportunities for investment into other renewable and sustainable energy technologies and resources in Uganda. The results can further influence policies related to preserving energy resources like forests and the ecosystem. While analyzing the energy efficiency of the incumbent technologies, we use a mixed-method research approach with survey data supported by insights from the sustainability transition theory. The rest of the paper is organized as follows; Section 2 presents the theoretical framework, Section 3 presents the materials and methods, Section 4 presents the results, section 5 discusses the results, and section 6 presents the conclusions and policy implications.

2. Theoretical framework

Theoretical considerations for analysing incumbent (existing) energy systems focus on technologies, infrastructures, institutions, and user practices as organs of change in this social-technical system (Turnheim & Sovacool, 2020). These structures are analysed to understand and identify technological weaknesses to be tackled by public policy in the process of societal transformation (Jensen, Goggins, Røpke, & Fahy, 2019). The structures are rooted within the complex system of the Multi-Level Perspective (MLP) that include regimes, niches, and landscape structures (Geels, 2002). The change process affecting incumbents results as a force originating from these three dynamic levels. For instance, landscape pressures such as biomass resource depletion, environmental degradation, nature conservation, emission reduction targets, and climate change can change the focus of regimes to target the development of niches in cleaner technological spaces like biogas, solar, and wind (Baumgartinger-Seiringer, 2022). Niches result from systems weaknesses that are identified through the destabilization of incumbents' established socio-technical regimes. The destabilization process creates windows of opportunity (niches) that actors exploit to create radical change (Geels, 2002). According to Joseph Schumpeter, the process of destabilizing incumbents is referred to as creative destruction. In the process of creative destruction, existing social-technical systems are broken down for new ones to emerge. This process renders incumbent technologies obsolete and might cause incumbent actors to withdraw from up-scaling as well as lose support from policy regimes (Geels & Kemp, 2007).

When regimes (institutions) shift to supporting the development and growth of niches then incumbents are disrupted and might completely collapse leading to the sustainable transformation of social-technical systems (van Mossel, van Rijnsoever, & Hekkert, 2018). Weakening incumbents can be caused by regimes switching resource allocation and investment benefits such as subsidies to the production of core niche technologies and imposing unfavourable conditions on the former (Steen & Weaver, 2017). While the existing technology may have become obsolete, moving away from it, and adopting the new might be hard for incumbents. Besides, many times, incumbents, benefit from the status quo, which leads them to protect their interests and thus are unlikely to support change and innovations. Incumbents are thus bonded to the already established practices and technologies which causes them to be slow to change, yet they are unlikely to produce novel ideas (Turnheim & Sovacool, 2020). This way, incumbents are seen as actors lagging behind technological change and societal transformation.

A shared and deep attachment to dominant regimes may cause incumbents to resist, slow down, or intentionally prevent the successful emergence of technological innovations and institutional structures that would enable the more rapid deployment of alternatives such as cleaner resources (Steen & Weaver, 2017). However, while the destabilization process destroys incumbents, it creates niche opportunities for social-technical transformations and might attract incumbent actors to join the process, especially where the alternative technologies have already acquired a share of the market (Baumgartinger-Seiringer, 2022). Patala, Korpivaara, Jalkala, Kuitunen, and Soppe (2019) contend that incumbents might show ambidextrous behaviour and simultaneously exert maintenance and change forces. As regime actors change their strategies incumbents can remain stuck in old ways or can use their power and resources to change when seeing value in engaging with transitions (Turnheim & Sovacool, 2020). This means that incumbents not only suppress but sometimes embrace disruptive innovations and exploit new opportunities. In this way, incumbent actors have sometimes been observed to contribute to niche-regime interactions and contribute to regime disintegration by pursuing divergent strategies (Steen & Weaver, 2017).

While using the framework of analyzing incumbents this study pursues a destabilization approach to identify weaknesses in the clean cooking technological systems that could be causing excessive biomass energy use in Uganda. The study uses food preparation routines embedded in cultural institutions to establish whether improved cookstoves reduce energy use. Santos, Spector, and Van der Heyden (2009) posit that cultural values and routines, influence technology and energy use and may cause established incumbents to inhibit the development and growth of niches and fail policy regimes supporting niches. Therefore, for transitions to succeed, they require significant changes to regime rules (policy goals and interaction patterns between government and industry) in ways favourable to niches, and rigid to cultural institutions as these normally hinder path-breaking innovations (Coenen & Díaz López, 2010). In the case of this study, suppressing excessive energy use might cause renewable energy niches and incumbent cook stove technologies to compete on unfair regime terms since the former is cleaner with extremely minimal risk to both the environment and human health. For any regimes to be successful in this case, a deeper analysis of the incumbent cookstove technologies like the one in this study is important. We conduct the analysis using the methods presented in the subsequent section.

3. Materials and Methods

To investigate the effect of food preparation routines and improved cookstoves on biomass energy use efficiency, we used cross-sectional survey data collected from three improved cookstove user segments (Institutions (primary and secondary schools), households and restaurants). To capture comprehensive details on food preparation routines and energy use relating to individual user segments, three different but related data collection instruments were developed. The survey instruments included different energy use indicators such as the type of food cooked, cooking time, amount of fuel used, and cost of fuel used for both ICS and non-ICS users. The survey was conducted using computer-assisted personal face-to-face interviews (CAPI). The instruments were thoroughly reviewed and then transformed into a digital format using the Open Data Kit (ODK) installed on Android tablets.

3.1. Survey data

3.1.1. Sampling and data collection

Survey data was gathered from 169 households, sixty-three institutions (schools) and 59 restaurants from July to October 2019 in four central districts in Uganda. Uganda is divided into four regions that include, Central, Eastern, Northern and Western regions. The four regions are further divided into 134 districts. From the 134 districts, we randomly sampled four districts that had the highest uptake of ICS in the central region and therefore, were the most convenient for this survey. (MoEaMD, 2015, 2019; UBOS, 2014, 2021). These included Kampala, Wakiso, Mukono and Luweero. For a better representation of energy use from rural and urban areas, we treated Kampala and Wakiso, as urban districts and Luweero and Mukono, as rural districts. In Luwero and Mukono, the survey was conducted in remote areas away from the urban centres of the two districts.

To gain access to the respondents, we worked with community leaders who introduced us to the different authorities in each respondent category. The interview partner representing the institutions was in most cases the head cook, headteacher or deputy headteacher. For restaurants, it was in all cases the owner, and for private households, it was in all cases the household head or the person with the main responsibility for food shopping and cooking. In the interviews, all participants were asked to indicate how many days they prepared meals in a typical week and the five dishes they prepared most and how often in a typical week they prepared them. Finally, all participants were asked to indicate the fuel sources they used for food preparation and the monthly costs they incurred for this. However, most respondents used ICS along with traditional cooking stoves (TCS), liquified petroleum gas (LPG), electricity, kerosene, or biogas. This was convenient for comparing energy use from the different technologies

3.1.2. Energy cost and energy use quantification

We obtained the data on the amount of fuel used by the different categories in various measurement units along with the costs per month. For instance, charcoal (trucks, full bags, half bags, basins, and smaller units), and firewood (trucks and bundles). Electricity was captured in Kwh, gas, and briquettes in kg, while kerosene was in litter. To quantify the energy equivalents of these different units, we adopted energy values of unprocessed biomass and other fuels recommended by Openshaw, Mastorakis, and Corbi (2015). From the recommendations, we made a short market survey to establish charcoal and firewood mass equivalents (kg) and prices (UGX). While in the field, we physically weighed full bags and smaller units of charcoal and bundles of firewood offered by five different vendors. We observed that the smaller units of charcoal were the ones fed into the basins at the time of selling to a customer. From the market, the number of full bags or half bags and logs or bundles of charcoal and firewood respectively, that filled a specific truck was ascertained. The track specifications were obtained from the data in the survey and the most common ones were Lorry, Canter, Elf and Forward. The trucks were quantities consumed by institutions while restaurants and households consumed bags, smaller units and bundles of charcoal and firewood respectively.

We physically weighed three different units of charcoal (full bag, half bag, and smaller units) and one unit of firewood (bundles), capturing 30 observations of quantity in kilograms (kg) and price in UGX for each unit. Measurements were obtained from five different firewood and charcoal vendors from different market locations. The averages of each category were computed and used to define the kilograms and later the megajoules in the survey data set. Based on REF we allocated energy values of 29.0 Mega Joules per kilogram (MJ/kg) and 18.7 MJ/kg for charcoal and firewood respectively. The results are shown in Table 1. The energy input values in Table 1 were used to compute the energy cost and use equivalents of the sample segments (institutions, restaurants, and households).

Table 1. Observed means of energy input values for charcoal and firewood (standard deviations in parentheses)

Fuel source	Local unit	Price (1000 UGX) per unit	Mass (kg) per unit	Price (1000 UGX) per kg	Specific energy (MJ/kg)	Energy (MJ) per 1000 UGX
Charcoal	Full bag	104.00 (5.16)	118.30 (25.64)	0.91 (0.16)	29.00	32.89 (6.21)
	Half bag	55.00 (3.33)	66.80 (6.71)	0.83 (0.10)	29.00	35.31 (3.92)
	Smaller bag	1.00 (0.00)	1.50 (0.50)	0.73 (0.25)	29.00	43.50 (14.50)
Firewood	Bundle	8.20 (4.66)	36.40 (21.09)	0.24 (0.05)	18.70	81.66 (22.95)

3.1.3. Fuel amount (kg), energy (MJ) and cost (UGX)

The survey captured data on the most used fuels, the number of times fuel is purchased per month and the amount of fuel purchased in a month. The fuel amount was captured in different units. Charcoal was captured in a full bag, half a bag, and a smaller bag. The benchmark mass values (kg) for these different units are presented in Table 1. A smaller bag was always measured in small plastic bags in the market. Firewood on the other hand was captured in bundles. We directly multiplied the fuel amounts obtained in the survey with the mass per unit (kg) from the market to obtain the amount of fuel in kilograms consumed by each segment. Energy (MJ) was calculated by multiplying the mass of firewood and charcoal with their respective specific energy values (MJ/kg) from Table 1. Since the survey data was based on estimated prices by the users, we adopted the price per kg unit obtained from the market and as presented in Table 1. The total fuel expenditure was then calculated by multiplying the total mass (in kg) with the cost price (in 1000 UGX) per kg.

3.1.4. Energy use estimates

To estimate energy use, we used the total number of people that fed on a meal prepared in a day (captured in the survey) in the three different segments (households, institutions, and restaurants). To calculate energy use per person meal, we used the total number of meals cooked in a day and the total number of people that fed on the meals cooked in a day. As described in the introduction of this paper, these meals are prepared using different technologies and different energy sources. Furthermore, the calculation of energy use per person meal differed between the three segments.

Institutions had boarding and day sections. In our analysis, we first computed the number of times the day schools cooked per day, separately from the boarding schools. When a school had only boarding students, the total number of meals per day was 3-4 for all students and 1-2 for staff members (this data was obtained in the survey). If the school had only day students, the total number fed was based on 1-2 meals per day (lunch only or breakfast and lunch) for all students and staff members. The survey also captured the number of boarding students and day students and the total number of staff employed in the institution. On average, schools with a day and a boarding section cooked three (3) meals per day (breakfast, lunch, and dinner) and indicated that day students and employees ate only two (2) meals per day (i.e., every extra meal was for boarding students). To find the number of times they cook a day for all students, we subtracted the extra meal. For boarding students only, we subtracted the number of times cooked per day from the number of times cooked per day for all students.

The number of days a restaurant cooks a week and the estimated number they feed per day were obtained in the survey. Some restaurants were open seven (7) others five (5) or six (6) days a week. This information was used to compute the number of personal meals for the restaurant segment. On the other hand, non-stay-home household members did not eat all meals at home during working days. In the survey, we captured data on the number of working, stay-home, and school-going household members together with the number of meals they consumed from home during the week. The information collected from all three segments was then used to calculate energy use per person meal and energy cost per person meal; these were our dependent variables of interest.

To assess the effects of the user segment, food, fuel source and stove type, a linear mixed model was estimated with log energy use per person meal produced as the dependent variable. Food and user ID were specified as random factors. User segment, fuel source and stove type were specified as fixed factors. Due to incomplete crossing, all effects of stove type and fuel source (either charcoal or firewood; the altogether 14 users of other fuel types were excluded) had to be nested under the user segment. The model was estimated by restricted maximum likelihood (REML). The same model was estimated again with log energy cost as the dependent variable.

4. Results

4.1. Cooking time

Qualitative findings revealed that institutions and restaurants cook for an average of fifteen hours a day. Cooking in institutions starts at 5:00 am and ends at 7:00 pm. Restaurants cook from 6:00 am to 9:00 pm. For all this time, cookstoves are burning. Households on the other hand cook on demand but on a day when all household members are at home, they cook for an average of 6 hours and their main meals are lunch and dinner. Households also indicated that different foods have different cooking times, different energy consumption and fuel costs although they had never thought of taking a record of this. The survey data further revealed that the most common food cooked across all segments is beans. Matooke, meat and posho were mainly common among restaurants and households.

4.2. Energy use

From the estimation of energy use, the model had an excellent fit ($R^2 = .90$, adjusted $R^2 = .90$, $-2 \ln L = 2893.51$, $BIC = 2984.89$). The random factors food (variance ratio = .31, Wald $p <$

.05) and user (variance ratio = 3.02, Wald $p < .001$) had significant effects. Among the fixed factors, user segment ($F_{2,228} = 47.05$, $p < .001$) and fuel source ($F_{2,229} = 18.05$, $p < .001$) had highly significant effects whereas stove type ($F_{3,228} = 1.18$, $p = .32$) and the interaction between the fuel source and stove type ($F_{2,228} = .94$, $p = .39$) were not significant.

4.3. Energy cost

The model estimation on energy cost also had an excellent fit ($R^2 = .94$, adjusted $R^2 = .94$, $-2 \ln L = 2808.02$, BIC = 2899.29). The random factors food (variance ratio = .31, Wald $p < .05$) and user (variance ratio = 2.19, Wald $p < .001$) had significant effects. Among the fixed factors, user segment ($F_{2,227} = 193.42$, $p < .001$) and fuel source ($F_{2,227} = 5.11$, $p < .01$) had significant effects whereas the effects of stove type ($F_{3,226} = .71$, $p = .55$) and the interaction between the fuel source and stove type ($F_{2,227} = 1.77$, $p = .17$) were not significant.

Estimated marginal means of both dependent variables are plotted in Figure 1 (as a function of food) and Figure 2 (as a function of the user segment, fuel source and stove type). Parameter estimates for both models are reported in Tables 3 and 4 in Appendix 1.

Compared across foods, the variation in energy efficiency was considerable (see Figure 1). The least energy-efficient food preparation (beans, at an average energy cost of 70.34 UGX per person meal and average energy use of 4.00 MJ per person meal) required on average four times as much as the most energy-efficient food preparation (fish, at an average energy cost of 17.79 UGX per person meal and average energy use of 1.40 MJ per person meal). Hence, the results support H1.

Compared across fuel source and stove type, we expected that improved cookstove technologies would mitigate excessive energy use. However, no such effect was found. Hence the results do not support H_2.

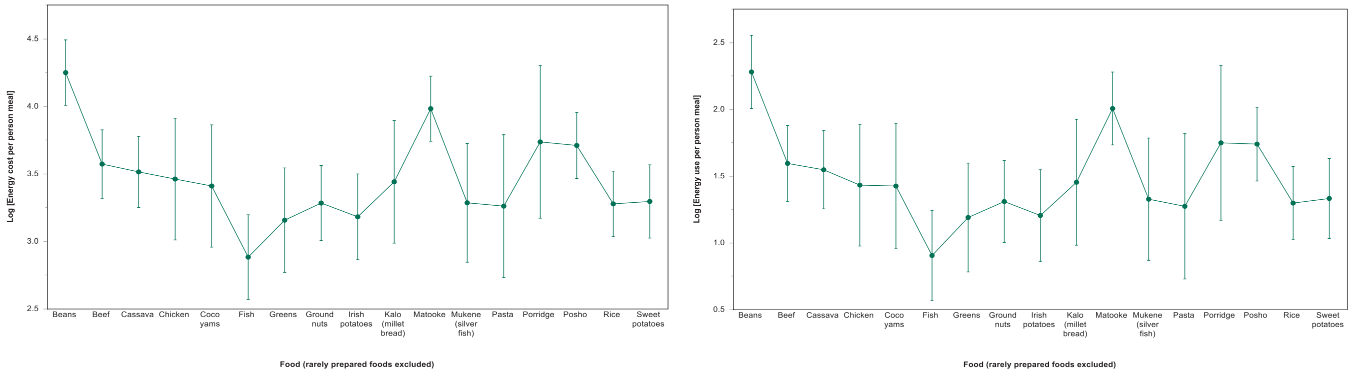

Figure 1. Estimated marginal means of energy cost (log UGX) and energy use (log MJ) per person meal as a function of the type of food prepared (error bars represent 95% confidence intervals)

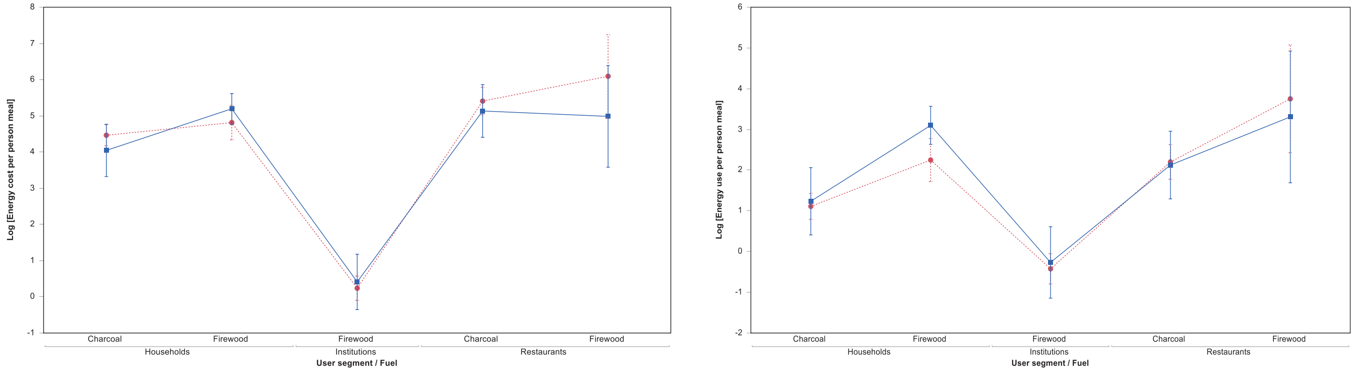

Figure 2. Estimated marginal means of energy cost (log UGX) and energy use (log MJ) per person meal, as a function of the user segment, fuel source and stove type (red: ICS, blue: no ICS); error bars represent 95% confidence intervals.

5. Discussions

In this study, we have investigated the effect of food preparation routines on energy use efficiency in Uganda. We have also investigated whether improved cookstoves reduce excessive energy use caused by food preparation routines in Uganda. Our findings have revealed that food preparation routines in Uganda lead to excessive energy use and cost. Figure 2 shows that institutional food service operations are to achieve scale efficiencies: energy cost and energy use per person meal produced are significantly lower compared to private households and restaurants (which were in our sample predominantly small operations). In H_2, we expected that the use of improved cookstove technology (ICS) would mitigate excessive energy use. However, the results indicate that improved cookstoves do not appear to alleviate problems of excessive energy use: there were no usage contexts in which ICS differed significantly from traditional cooking technologies. This is a counterintuitive result, considering the many findings in the previous literature that reveal ICS as a clean and efficient technology with the capability to reduce excessive energy use (Johnson et al., 2013; Loo et al., 2016). This manifests a system's weakness for the incumbent clean cooking technologies in Uganda. However, our results are identical to the findings of Kishore and Ramana (2002) and Nepal et al. (2011). The results also explain the observations by (UBOS, 2015, 2021) where no significant reduction has been observed in biomass energy use since the introduction of improved cookstoves in Uganda. These results could further explain why there is continued depletion of forest resources in Uganda and why attempts to increase access to clean energy have been unsuccessful in many developing countries (Namugenyi et al., 2022; Zhang, 2022).

Nevertheless, the theoretical framework in this study provokes the analysis of incumbent systems to identify weaknesses that could be used to destabilize the old system and cause the emergence of a new one (Geels, 2002). Weaknesses in the incumbent system create windows of opportunity for the regime and niche actors (Geels & Kemp, 2007). For the incumbent clean cooking technologies in Uganda not being energy and cost-efficient is a weakness that directly communicates to the regime and niche actors that the technologies are mature, inefficient, and unsustainable and thus need urgent transitioning to cleaner and sustainable energy technologies. During the transition process, weaknesses of the incumbent system guide regime actors to develop unfair policies for incumbents and fair to the niche systems (Steen & Weaver, 2017). Related to this study, niche actors could explore alternative cleaner solutions like biogas, solar and wind energy as the regimes support the same. This will help to phase out the incumbent inefficient improved cookstoves, pave way for cleaner solutions and accelerate access to clean energy in Uganda. Besides, the revised energy policy for Uganda strategized a key issue to promote and incentivize switching from biomass to alternative efficient fuels and technologies like LPG, biogas, electric pressure cookers and solar cookers (MoEaMD, 2019 4.5, 4.4.1, 7). The findings in this study could thus be important in deciding the directionality of implementing this policy strategy.

5.1. Limitations and future research

Despite making a comprehensive examination of the energy efficiency of improved cookstoves and revealing noteworthy results with implications for biomass energy use, the authors identified some limitations. First, the study was done across three user segments which required developing different tools for each segment to capture the exact information related to the cooking routines of the targeted users. This required too much time to prepare. Second, the study was conducted during school season in Uganda, particularly for schools the targeted respondents were always found busy, and this required us to make future appointments and travel to the schools more than once which consumed a lot of time. For the households, the children were in school at the time which limited our observation of family sizes. Third, some respondents used mixed energy sources for which they did not keep a record of the proportion of energy and cost allocated to each of them. This could have caused ambiguity in reporting the expenditures on each fuel source used. Forth, some households could not allow us to observe their cooking places for confidentiality which limited our observation findings. Finally, the study focuses on analysing only incumbent improved cookstoves. There are however other clean cooking technologies in Uganda like biogas and eco-solar-aided stoves that the study does not explore but instead recommends as alternative solutions to energy efficiency and clean cooking. Future research should also explore the energy efficiency of these alternative sources concerning the cooking routines in Uganda.

6. Conclusions and policy implications

This article aimed to investigate whether food preparation routines lead to excessive energy use and whether the incumbent clean cooking technologies (improved cookstoves) reduce excessive biomass energy use when deployed in real-life settings (as opposed to laboratory conditions) in the three main biomass user segments in Uganda. We gathered micro-level evidence on food preparation routines to empirically measure energy use and energy cost efficiency of improved cookstoves. We estimated energy use and energy cost per person meal. The component of food preparation routines is embedded in the cultural institutions and is important when deciding which stove type to use implying that it affects energy use. This kind of assessment has been overlooked by many scholars measuring ICS efficiency; our review of the relevant literature revealed that scholars and stove developers have ignored cooking cultures such as the ones in Uganda and their effect on energy and technology use.

This paper finds that food preparation routines with increased cooking time led to excessive energy use in Uganda. The results further reveal that improved cookstoves do not appear to alleviate such problems of excessive energy use: there were no usage contexts in which improved cookstoves differed significantly from traditional cooking technologies. The results are important for transition actors such as entrepreneurs and policymakers. To the entrepreneurs, the results are important to consider investment into alternative clean energy technologies like biogas options. To the policymakers, the findings are important to guide the directionality of regimes such as switching support to the development of cleaner energy solutions while being unfair to the improved cookstoves incumbents. Incumbents could however consider phasing out the improved cookstoves and investing in niche opportunities such as the unexploited biogas solutions. A sustainable transition through these recommendations could help improve resource management, reduce depletion, and mitigate climate change in Uganda. The transition from mature inefficient and unsustainable cooking technologies could also accelerate the achievement of SDG 7.

Acknowledgements

The authors would like to thank the NORAD/NOHED project for funding this work.

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Appendix 1

Figure 1: Traditional preparation of matooke

Appendix 2

Table 3. REML parameter estimates: energy costs (log UGX) per person meal

Fixed-effect terms	*b*	*SE*	*t*	*p*	95% CI	
					Lower	Upper
Intercept	3.453	.147	23.490	.000	3.161	3.746
User segment [Households]	1.176	.133	8.840	.000	.914	1.438
User segment [Institutions]	-3.127	.163	-19.210	.000	-3.448	-2.806
User segment [Households]: Stove type [ICS]	.009	.119	.080	.940	-.225	.243
User segment [Institutions]: Stove type [ICS]	-.087	.201	-.430	.667	-.484	.310
User segment [Restaurants]: Stove type [ICS]	.345	.248	1.390	.166	-.144	.835
User segment [Households]: Fuel [Charcoal]	-.375	.119	-3.150	.002	-.609	-.140
User segment [Restaurants]: Fuel [Charcoal]	-.134	.248	-.540	.590	-.623	.355
User segment [Households]: Stove type [ICS] & Fuel [Charcoal]	.200	.119	1.690	.093	-.034	.434
User segment [Restaurants]: Stove type [ICS] & Fuel [Charcoal]	-.209	.248	-.840	.402	-.698	.281
Random factors	Variance ratio	Variance component	*SE*	*p*	95% CI	
					Lower	Upper
User ID	2.193	.905	.094	.000	.721	1.089
Food (rarely prepared foods excluded)	.312	.129	.051	.011	.029	.228
Residual		.413	.020		.377	.455
Total		1.447	.108		1.256	1.684
R^2	.94					
R^2 (adjusted)	.94					

Table 4. REML parameter estimates: energy use (log MJ) per person meal

Fixed-effect terms	*b*	*SE*	*t*	*p*	95% CI	
					Lower	Upper
Intercept	1.475	.161	9.170	.000	1.156	1.794
User segment [Households]	.448	.153	2.930	.004	.147	.750
User segment [Institutions]	-1.819	.188	-9.680	.000	-2.190	-1.449
User segment [Households]: Stove type [ICS]	-.244	.136	-1.800	.074	-.512	.024
User segment [Institutions]: Stove type [ICS]	-.078	.233	-.340	.737	-.537	.380
User segment [Restaurants]: Stove type [ICS]	.130	.287	.450	.651	-.435	.695
User segment [Households]: Fuel [Charcoal]	-.750	.136	-5.520	.000	-1.018	-.482
User segment [Restaurants]: Fuel [Charcoal]	-.683	.287	-2.380	.018	-1.248	-.118
User segment [Households]: Stove type [ICS] & Fuel [Charcoal]	.181	.136	1.330	.183	-.086	.449
User segment [Restaurants]: Stove type [ICS] & Fuel [Charcoal]	-.092	.287	-.320	.749	-.657	.473
Random factors	Variance ratio	Variance component	*SE*	*p*	95% CI	
					Lower	Upper
User ID	3.017	1.238	.125	.000	.993	1.483
Food (rarely prepared foods excluded)	.314	.129	.051	.011	.029	.228
Residual		.410	.020		.374	.452
Total		1.777	.136		1.539	2.076
R^2	.90					
R^2 (adjusted)	.90					

Paper III

Journal of Cleaner Production 333 (2022) 130135

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Realising the transition to bioenergy: Integrating entrepreneurial business models into the biogas socio-technical system in Uganda

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ARTICLE INFO

Handling Editor: Yutao Wang

Keywords:
Transition
Entrepreneurial
Business model innovation
Socio-technical system
Biogas
Uganda

ABSTRACT

This study assesses the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit. Our findings reveal that existing research has neglected the entrepreneurial potential in biogas energy that could increase energy supply and access in developing countries. Therefore, using a multimethod approach, the paper provides a comprehensive analysis of how an entrepreneurial business model could be developed and integrated into the biogas socio-technical system in Uganda. The analysis from the transitional model canvas shows that current biogas users have a relatively high satisfaction rate (50%) and with the adoption of the entrepreneurial business model this satisfaction could be captured on a wider social spectrum. Results from the feasibility study indicate that by sourcing materials locally, system builders (entrepreneurs) achieve a marginal cost reduction of 64% compared to when they are imported. Both findings from the transitional model canvas and the feasibility study indicate a high probability of not only reducing the supply gap but also a reliable energy source for developing countries and a potential for income generation and employment for the wider society.

1. Introduction

Households in rural areas of Uganda still have very limited access to clean energy and cooking under devastating and undignified conditions. Cooking places have turned black due to the accumulation of soot (black carbon) which endangers household health (Appendix II). Moreover, firewood resources are depleting due to clearing forests for agriculture and settlement. Government reports and previous research indicate that the use of clean fuels like biogas, liquefied petroleum gas and electricity for cooking and lighting is insignificant among Ugandan households (MoEaMD, 2015, 2019; UBOS, 2021). According to Kees and Eije (2018) and UBOS (2021), low-grade solid biomass fuels like firewood and charcoal account for about 94% of the total energy consumption. Kerosene[1] is still the major source of lighting for more than 50% of households in rural areas and 16% in urban areas with a user satisfaction rate of 46.2% (MoEaMD, 2019, 2002; UNDP, 2020). The routine of using solid biomass has directed entrepreneurship and innovation activities towards the production of biomass energy conversion technologies such as improved cookstoves. On the other hand, UNDP (2020) found that biogas producing households were at a 50% rate satisfied with its use and that agricultural feedstocks are highly available and reliable for biogas production, although this option is not fully exploited.

Biogas is a clean energy fuel that burns with a “blue flame” (Amone, 2014; Foell et al., 2011; Kishore and Ramana, 2002; Rehfuess, 2006). In Uganda, biogas energy is mainly promoted in private farming households using “free of cost” and “free of service” business models (Clemens, Bailis, Nyambane, & Ndung’u, 2018; Rupf et al., 2016). “Free of cost” and “free of service” is a promotion model where biogas technology is donated freely by the state and non-profit organisations (NGOs) to livestock-keeping households to produce biogas energy. This means that private households are the major producers and consumers of bioproducts (biogas and slurry). Besides constructing biodigesters, households are given a free training service on how to operate the technology to produce gas and slurry. Households use the gas for cooking and

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[1] Kerosene is a “dirty” fuel; it produces soot (black carbon) that affects the health of users and their household members.

https://doi.org/10.1016/j.jclepro.2021.130135
Received 31 March 2021; Received in revised form 15 November 2021; Accepted 13 December 2021

lighting, and the slurry for fertiliser to boost crop production. However, the free of cost, free of service model does not motivate the creation and development of productive (commercial) ventures in the current biogas supply chain. Instead, it creates a situation where the households do not care to maintain the technology nor attend to repair activities once it breaks down. After all, they do not have any financial stakes invested and thus have little to lose. In the long run, the technology seems to get dis-adopted (Lwiza et al., 2017; Tumusiime et al., 2019).

The policy of targeting private households to promote biogas runs the risk of compromising the direct benefits of this socio-technical system to the wider society. Nevertheless, Uganda's energy policy aims to promote the development of renewable energy systems for both small and large-scale applications (MoEaMD, 2019, 2002). Even though research shows that this energy source has a high potential to cover the unmet energy needs of both the rural and urban population (Kabyanga et al., 2018; Okello et al., 2013), the policy framework does not yield productive biogas supply chains. The policy is geared towards increasing the generation and supply of renewables with a preference for hydropower production. Whilst the country generates surplus electricity, it is unaffordable due to low incomes, exacerbated by the annual population growth rate of 3.6% (The World Bank, 2019). Therefore, integrating entrepreneurial business models into biogas energy supply chains is critical to increasing energy supply and informing innovation and energy policy research in developing countries (FAO, 2018; Rupf et al., 2016). Entrepreneurial business models refer to strategies geared towards the creation and development of commercial (productive) business ventures (Andersén et al., 2015). Consequently, using entrepreneurial business model approaches to promote biogas is likely to lead to the realization of a sustainable transition to bioenergy and increasing access to clean energy in the developing world (Clemens et al., 2018; Kabyanga et al., 2018; Okello et al., 2013).

Current and past research on the biogas socio-technical system has assessed its economic viability to private households (Kabyanga et al., 2018), the benefits of its use as a clean energy source (Carrosio, 2013), and feasible technologies and feedstocks for its production (Rupf et al., 2016). Besides, the biogas socio-technical system has been extensively conceptualized using institutional theories (Truffer et al., 2009) fuel stacking theories (Sabyrbekov and Ukueva, 2019) economic evaluation models (Walekhwa et al., 2014), and other policy dynamics (Markard et al., 2016). It could be argued though that these studies lack stringent empirical analyses of objective data on the biogas energy sub-sector performance, which may have limited their relevance for bioenergy business developers. Furthermore, it appears that no studies have explored the integration of entrepreneurial business models into the biogas socio-technical system to exploit its potential for wider social benefits. Relatedly, there is a lack of knowledge on how entrepreneurial models, at a practical level, could be effectuated especially in developing countries. This has left would-be entrepreneurs in developing countries thinking that biogas businesses are lacking commercial feasibility. To address these shortcomings and misunderstandings, this paper develops a model that shows how a commercial biogas supply chain could be pursued (effectuated) to realize a sustainable transition to bioenergy. Ray, Mohanty, and Mohanty (2016) and (FAO, 2018) posit that bottling (containerizing) biogas in portable cylinders is a suitable strategy for building commercial ventures. The commercial ventures could also potentially promote other sectors of the economy like agriculture, health and education. Clemens et al. (2018) and Rupf et al. (2016) suggest that research for policy development and implementation of programs directed towards bottling biogas is important for such commercial ventures. Therefore, the purpose of this paper *is to assess the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit.*

This article is at the intersection of research, innovation, and impact (Gulbrandsen, 2011; Lundvall and Borrás, 2005) and seeks to make the following empirical and policy contributions. First, the paper is action research-oriented since it aims to solve a real-world problem (Wittmayer et al., 2014). The paper analyses and presents a practical solution that developing countries could explore to increase energy access. Increasing energy access can improve living standards that lead to social well-being. In this way, the paper builds on the works of other scholars that have discussed the role of university research in innovation and the use of scientific knowledge in society. Secondly, the ideas presented here contribute to sustainable development goal 7 (UN General Assembly, 2015 7.a, 7.b). Energy and innovation policymakers in developing countries could use such knowledge to develop strategies of how to increase energy access in low-income communities through innovations that lead to sustainability transitions. The rest of the paper is structured as follows. Section 2 discusses the theoretical framework concepts used in framing the study. Section 3 explains the methodology used in the study. Section 4 presents the results. Section 5 discusses the findings and limitations of the study and provides conclusions and recommendations.

2. Theoretical framework and transitional model canvas

Society functions in a mix of complicated socio-technical systems like energy supply, agricultural production, and transport infrastructure. These systems require constant transitions to cause a radical change in society (Fallde and Eklund, 2015; van Rijnsoever and Leendertse, 2020). Coenen and Díaz López (2010) define transitions as a system-wide co-evolution of new technologies, alterations in markets and user practices, policy and cultural dialogues and governing institutions. They further posit that in the context of societal functions (like energy supply and transportation) socio-technical systems comprise the production, dissemination and use of technology. They also comprise elements like knowledge, capital, labour, and cultural attributes that foster successful transformations. Geels (2002), Geels (2011) and Köhler et al. (2019) assert that socio-technical systems are organised under a multi-level perspective framework, in three varying dynamic levels that include technological niches, socio-technical regimes, and the socio-technical landscape.

Coenen and Díaz López (2010) assert that technological niches and socio-technical regimes consist of similar elements but differ in scope and stability, here the former is more diverse and heterogeneous in rules and innovation activities. Regimes encompass a highly complex structure that includes scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, established user needs, institutions and infrastructures. The organisation of this complex offers stable rules that allow actors to coordinate activities, to maintain and improve the socio-technical system through incremental innovation. On the other hand, the nature of niches makes them unstable thus causing disruptive and more radical innovations (Fallde and Eklund, 2015). The socio-technical landscape consists of slow-changing external factors that condition the interaction of niche and regime activities (Köhler et al., 2019; Markard et al., 2012).

The multi-level framework explains the transformation process of socio-technical systems. It consists of an incumbent (existing) system that is disrupted for a new system to emerge. Disruptions within the incumbent system create niches that a small group of actors known as systems builders (entrepreneurs) exploit during the transition process to cause radical change (Fallde and Eklund, 2015; van Rijnsoever and Leendertse, 2020). Actors exchange resources, create networks and markets and form productive supply chains using business model innovation approaches (Fallde and Eklund, 2015; Massa and Tucci, 2013). Business model innovation allows socio-technical systems to create, capture and deliver economic and social value to users (Osterwalder et al., 2011). It involves a structure of actor-networks and linkages to carry out transition activities that pertain to the content (products, activities, resources, and capabilities) required to capture the value that drives socio-technical transitions (Amit and Zott, 2012; Massa and Tucci, 2013).

Importantly, changes framed and explained by the multi-level framework can be enacted using business model innovation approaches (Sandberg and Alvesson, 2021). According to van Rijnsoever and Leendertse (2020), the multi-level and business model innovation frameworks can be combined using a transition model canvas (TMC) inspired by the traditional business model canvas of Osterwalder et al. (2011) the TMC is a practical tool used to analyze and enact socio-technical transitions. The TMC tool is made up of four quadrants represented by the transitional goal, the incumbent (existing system), the niche system and the landscape structure. Within the socio-technical system, TMC analyses relations for entrepreneurial prospects, identify and evaluate different strategies for a successful transition. This analysis allows the socio-technical system to address and adapt to uncertainties during the transition through entrepreneurial processes. Therefore, the TMC assesses the existing (incumbent) system to identify the disruptions (vulnerabilities) that become the focus of the niche system. The TMC model, however, does not account for the key activities for the transition which this study deems significant for a sustainable transition process.

Whilst the concepts presented in the TMC are extracted from the multi-level and business model innovation frameworks, strategic resources for developing the biogas upgrading technology may not be easily identified by would-be entrepreneurs. According to Klein (1990), identifying key resources for executing entrepreneurial tasks requires a feasibility analysis. Klein defines feasibility as resources that are available and accessible under a firm's control to perform a task. Borrowing from the experimental learning literature, availability and accessibility respectively denote possession and retrievability of information about the existence of resources. Resources are defined as commodities that enable the accomplishment of an objective. Drawing from economics, resources include physical assets (raw materials, capital, equipment, supplies, land, and information) and human resources (knowledge, skills, and abilities). Resources available for accomplishing a certain task may be scarce or abundant. Resources may be available and accessible or available but inaccessible. Resource scarcity may cause inaccessibility which limits entrepreneurial activity and innovation of a country. Resource abundance, on the other hand, permits stimulation and achievement of entrepreneurial ventures, the satisfaction of which is maximized by task difficulty.

The biogas socio-technical system in this study is examined on four levels. Level 1 summarises the transition goal, which is also the societal challenge that the niche system aims to address. Level 2 analyses the incumbent or existing biogas system. The incumbent consists of the key elements and interactions, strengths and vulnerabilities and strategies. Key elements and interactions outline the current supply chain actors and the institutional demands that include policy objectives, it also shows the system interactions that identifies user insights and behaviours. The strengths give an overview of the factors that are keeping the existing system in operation and how it is maintained and the vulnerabilities indicate the weaknesses which the niche system may exploit in the process of transition. The last part of level 2 reveals the strategies the incumbent system can use to defend its position to stay in operation and the strategies that could inhibit the niche system from taking over the supply chain activities.

Level 3 examines the niche system which is also the entrepreneurial model that this research proposes. This section presents the focus, key elements and interactions which comprise (a) the focus of the niche which is also the proposed entrepreneurial opportunity that should be pursued if Uganda is to realize a successful transition to bioenergy, (b) the actors including the ones from the incumbent and the ones that will join the entrepreneurial niche respectively, (c) the institutions responsible for making policy and the demands they impose as well as the sectoral regimes, and (d) the interactions that the different actors could get involved in like collaborations and competition for funding to aid the transition process. The niche system also specifies some strengths that would leverage the entrepreneurial model proposed. Borrowing from economics, strengths are qualities and capabilities that give organisations a competitive advantage. In this model strengths are the factors or structural challenges like wood scarcity as well as limited energy access that purifying and bottling biogas seeks to address. Vulnerabilities and uncertainties on the other hand are weaknesses and risks that the system builders are likely to face, but these also prompts the strategies to destabilize the incumbent system and strengthen the niche in the next section. The last part of the niche system states the strategic resources both available and missing that will help the systems builders to destabilize the incumbent system while strengthening the niche system. On level 4, the social-technical landscape structure under which the existing and the niche systems operate is outlined. In the following section, we present the methods that were used to analyze the entrepreneurial opportunity mapped in the TMC and assess the feasibility of purifying and bottling biogas in Uganda.

3. Materials and methods

This study employed a multimethod approach, comprising of semi-structured interviews, nonparticipant observation, document analysis and a feasibility study.

3.1. Semi-structured interviews

The study is built on qualitative findings that were part of a cross-section quantitative survey, that was administered through computer-assisted personal face-to-face interviews (CAPI) between July and October 2019 in the central Uganda districts of Kampala, Luwero, Wakiso and Mukono. The survey was intended to find out the cooking routines and energy use patterns among users and non-users of improved cookstoves in Uganda. The chosen study districts represent a high concentration of improved cookstove entrepreneurs registered with the Uganda National Alliance for Clean cooking. The Uganda national household survey and census UBOS (2021) also shows that adoption of Improved cookstove technologies has been fairly high in the chosen survey areas as compared to other districts therefore, they were the most convenient for our study. For a better representation of energy use from rural and urban areas, we treated Kampala and Wakiso, as urban districts and Luweero and Mukono, as rural districts. Kampala and Wakiso are equally the biggest central business districts in Uganda with the fasted growing population of modern households and restaurants (UBOS, 2014, 2015). The survey findings revealed that at least eight out of every ten households that had been interviewed in the four districts testified that firewood had become scarce. Participants reported that due to the scarcity of firewood, they were using wet wood to cook which produced a lot of smoke that caused itchy eyes and cough, thus making their cooking times very frustrating. Furthermore, from the household interviews and observations, survey results showed that households that cooked with biogas had a clean and smoke free environment compared to households that were using solid biomass (firewood). These findings contributed to further investigations with key actors like biomass technology entrepreneurs and heads of institutions, through key informant interviews.

3.1.1. Sampling and key informant selection

This study's sample selection procedure followed several characteristics that the research team defined from the obtained sample of institutions (schools) in the main survey. The main survey obtained sample responses from 169 rural and urban households, 59 restaurants and 63 institutions (schools). The general observations from the main survey revealed that school headteachers exhibited high-quality knowledge of biomass energy and technology usage and related challenges. Therefore, this led to the selection of the schools' headteachers into a further in-depth key informant discussion. Nevertheless, the team considered other characteristics that included (a) the main survey must have been conducted with strictly the school headteacher and not the head cook or deputy, (b) the school must have a boarding section since schools with a boarding section used more firewood as they prepared a minimum of 3 meals a day for 7 days a week, (c) the school must be a secondary or vocational institution because the headteachers of such institutions were mostly degree holders and more, and (d) the school should have a population of 1000 students or more, schools with such a population had more challenges related to finding firewood and dealing with fuel suppliers. This would thus put them in a better position to discuss potential solutions of how to overcome such challenges. A combination of these different attributes led to a sample of 6 schools in Luwero, four schools in Kampala, six schools in Wakiso and five schools in Mukono, reducing our sample to 21 institutions. The lead researcher contacted all the 21 headteachers through a telephone call for a key informant interview appointment but only ten confirmed their availability at an agreed date. During the interviews, eight headteachers agreed to an audio recording of the interviews while two declined and the researcher recorded their responses in a notebook.

To validate the robustness of the findings from the user side, and widen the scope for ideas on the best alternative energy source to solid biomass, we interviewed three biomass technology entrepreneurs. These entrepreneurs included one manufacture of improved cookstoves, one briquet stone producer and one biodigester construction engineer. These three entrepreneurs were identified and selected through contact references obtained from an admin of a renewable energy WhatsApp group known as *"development revolvers"*. The WhatsApp group admin had an established relationship with some biomass technology entrepreneurs who were involved in making different biomass techs like building biodigesters, making improved cookstoves and briquettes. When he was contacted, he provided us with a list of nine entrepreneurs known to him. All nine entrepreneurs were contacted by the lead researcher but only 3 managed to make time for the interviews. These three interviews were equally recorded and later transcribed. While conducting these interviews, the interviewers used "how might we" questions. For example, "how might we help rural households find better cooking solutions that will improve their general quality of life?" "How might we" questions are intended to help ideate creative solutions to a problem (Kelley et al., 2001). These types of questions also provide in-depth analysis and deeper insights into the different users' energy needs and help to explore feasible solutions to users pain points. The key informant tool included questions related to (a) biomass use and the environment, (b) biomass use and improved cookstove technologies and (c) other technologies on which this papers main theme is nested. The key informant interview guide is appended in Appendix 3 of this article.

3.2. *Non-participant observations*

This method involved observing participants without getting actively involved with them. When conducting the interviews, a team of six interviewers moved in pairs of two. One was to conduct face to face interviews and the other was to observe and take pictures without actively interacting with the respondent. The observer moved around the respondents cooking areas with permission, to take pictures but also took notes on responses elaborated by the interviewee to save on the interview time. This helped to capture qualitative data beyond the survey tool most of which is used in this paper. Representative households were randomly selected through home visits, with the coordination of a local village leader. The observations were used to establish the cooking conditions of households and build a case for which the entrepreneurial model proposed in this study is inclined.

3.3. *Document analysis and case study*

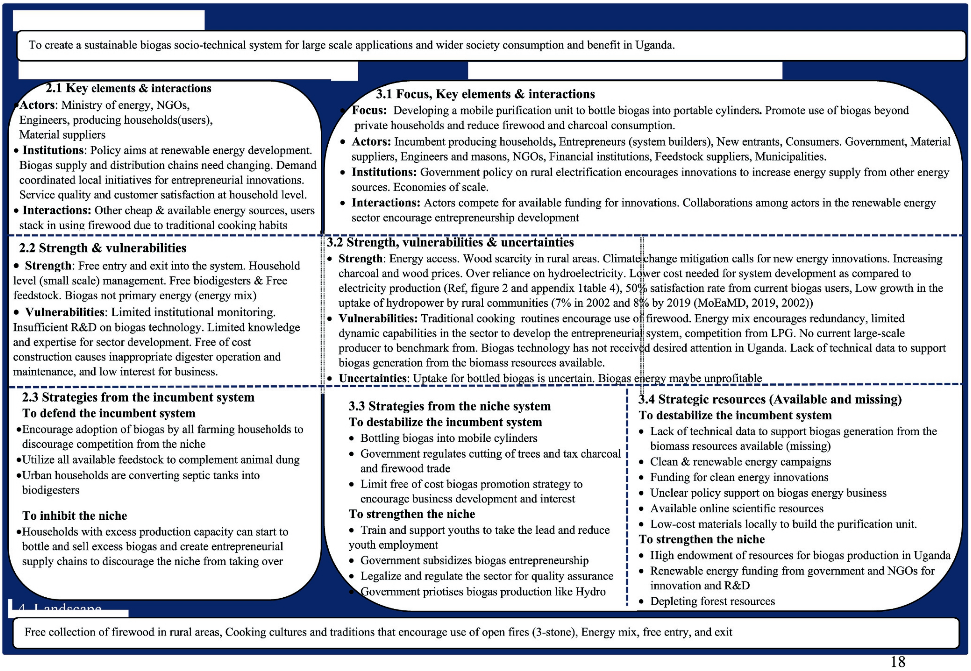
After the face to face interviews and observation sessions, the researchers delved into a thorough and superficial (skimming) examination of different documents to clearly understand the biogas case study. Document analysis is a systematic procedure for reviewing or evaluating documents both printed and electronic (computer-based and Internet-transmitted) material. Davie and Wyatt (2013) state that documents provide background information as well as historical insights that help to understand the historical roots of specific societal challenges and conditions in the context of the research endeavour. Second, documents are social products of collective, organized action. Therefore, they serve as a means of tracking change and development within a social system (Bowen, 2009). Several documents including organizational, institutional reports; national statistics; journals; previous studies were examined to establish the state of the art on the energy supply socio-technical system in Uganda. The analysis here focused on themes like energy technology innovation, biogas promotion and supply methods, and energy access dynamics in the country. Critical insights on the models used in promoting different energy technologies by the state and industry were captured with a bias on biogas technology. This analytical procedure involved finding, selecting, appraising (making sense of), and synthesizing data contained in documents. Like other analytical methods in qualitative research, in document analysis, examination and interpretation of information to elicit meaning, gain understanding, and develop empirical knowledge on which a case is built was vital.

According to Kutsyuruba (2017), document analysis is predominantly applicable to qualitative and intensive studies to produce rich descriptions of a single phenomenon, develop understanding and discover insights relevant to the research problem. When analyzing the documents, the original purpose of the document, the reason it was produced, and the target audience was established. Information about the author of the document and the source of information was also helpful in the assessment of a document. The documents selected for this analysis followed the researchers established procedures to ascertain whether the content of the documents fits into the theoretical framework of the study. For instance, the model in which the TMC for biogas technology in Uganda is presented (see Fig. 1) was based on the multi-level perspective (MLP) and business model innovation (BMI) frameworks and discussed with data from the government of Uganda energy and policy documents. The transitional goal in the TMC was extracted from the energy policy for Uganda of 2002, 2019 and other institutional documents. Other TMC components were extracted from different government and non-government documents as highlighted in Table 1. This study did not intend to delve into a deeper discussion of the multi-level Perspective and business model innovation concepts but rather use their concepts to develop and discuss the TMC for the technology under study. Table 1 shows a summary of the key documents analysed to support the anecdotal findings from the qualitative interviews and observations. The table also shows the levels of the TMC that the data from the documents was used to build.

3.4. *Feasibility analysis*

Based on anecdotal evidence, biogas upgrading in Uganda seems a difficult task because of limited accessibility (retrievability) of information about the availability (possession) of resources within the country. Nevertheless, using biogas energy is making significant strides in the developed world, where its mainly used as clean energy in the transport industry. For example in Sweden (Karlsson et al., 2017; Lantz et al., 2007), Italy (Sahota et al., 2018), rural electrification for cooking and lighting in China (Chen et al., 2010), India and Pakistan (Ilyas, 2006). This means that resources for upgrading biogas are available and accessible in developing countries too. Therefore, conducting a feasibility study of the materials and cost considerations in this study for local and international scenarios (online. Alibababa.com) confirms this hypothesis and may minimize task difficulty.

To determine the availability and accessibility of the materials for purifying and upgrading biogas, we conducted a feasibility study of the key resources (materials and costs) comparing a local sourcing scenario to international sourcing (importing) scenario. For the local scenario, a ten days survey was carried out in Uganda's central district of Kampala that resulted in obtaining costs from 20 different material suppliers. The



To create a sustainable biogas socio-technical system for large scale applications and wider society consumption and benefit in Uganda.

2.1 Key elements & interactions

- **Actors**: Ministry of energy, NGOs, Engineers, producing households(users), Material suppliers
- **Institutions**: Policy aims at renewable energy development. Biogas supply and distribution chains need changing. Demand coordinated local initiatives for entrepreneurial innovations. Service quality and customer satisfaction at household level.
- **Interactions:** Other cheap & available energy sources, users stack in using firewood due to traditional cooking habits

3.1 Focus, Key elements & interactions

- **Focus:** Developing a mobile purification unit to bottle biogas into portable cylinders**.** Promote use of biogas beyond private households and reduce firewood and charcoal consumption.
- **Actors:** Incumbent producing households**,** Entrepreneurs (system builders), New entrants, Consumers. Government, Material suppliers, Engineers and masons, NGOs, Financial institutions, Feedstock suppliers, Municipalities.
- **Institutions:** Government policy on rural electrification encourages innovations to increase energy supply from other energy sources. Economies of scale.
- **Interactions:** Actors compete for available funding for innovations. Collaborations among actors in the renewable energy sector encourage entrepreneurship development

2.2 Strength & vulnerabilities

- **Strength**: Free entry and exit into the system. Household level (small scale) management. Free biodigesters & Free feedstock. Biogas not primary energy (energy mix)
- **Vulnerabilities**: Limited institutional monitoring. Insufficient R&D on biogas technology. Limited knowledge and expertise for sector development. Free of cost construction causes inappropriate digester operation and maintenance, and low interest for business.

3.2 Strength, vulnerabilities & uncertainties

- **Strength**: Energy access. Wood scarcity in rural areas. Climate change mitigation calls for new energy innovations. Increasing charcoal and wood prices. Over reliance on hydroelectricity. Lower cost needed for system development as compared to electricity production (Ref, figure 2 and appendix 1table 4), 50% satisfaction rate from current biogas users, Low growth in the uptake of hydropower by rural communities (7% in 2002 and 8% by 2019 (MoEaMD, 2019, 2002))
- **Vulnerabilities:** Traditional cooking routines encourage use of firewood. Energy mix encourages redundancy, limited dynamic capabilities in the sector to develop the entrepreneurial system, competition from LPG. No current large-scale producer to benchmark from. Biogas technology has not received desired attention in Uganda. Lack of technical data to support biogas generation from the biomass resources available.
- **Uncertainties**: Uptake for bottled biogas is uncertain. Biogas energy maybe unprofitable

2.3 Strategies from the incumbent system

To defend the incumbent system

- Encourage adoption of biogas by all farming households to discourage competition from the niche
- Utilize all available feedstock to complement animal dung
- Urban households are converting septic tanks into biodigesters

To inhibit the niche

- Households with excess production capacity can start to bottle and sell excess biogas and create entrepreneurial supply chains to discourage the niche from taking over

3.3 Strategies from the niche system

To destabilize the incumbent system

- Bottling biogas into mobile cylinders
- Government regulates cutting of trees and tax charcoal and firewood trade
- Limit free of cost biogas promotion strategy to encourage business development and interest

To strengthen the niche

- Train and support youths to take the lead and reduce youth employment
- Government subsidizes biogas entrepreneurship
- Legalize and regulate the sector for quality assurance
- Government priotises biogas production like Hydro

3.4 Strategic resources (Available and missing)

To destabilize the incumbent system

- Lack of technical data to support biogas generation from the biomass resources available (missing)
- Clean & renewable energy campaigns
- Funding for clean energy innovations
- Unclear policy support on biogas energy business
- Available online scientific resources
- Low-cost materials locally to build the purification unit.

To strengthen the niche

- High endowment of resources for biogas production in Uganda
- Renewable energy funding from government and NGOs for innovation and R&D
- Depleting forest resources

4. Landscape

Free collection of firewood in rural areas, Cooking cultures and traditions that encourage use of open fires (3-stone), Energy mix, free entry, and exit

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Fig. 1. Transitional model canvas for biogas technology in Uganda.

cost was then aggregated into four supplier categories at data sorting. All the materials were available in Kampala and at affordable costs, although they were scattered within different shops. The authors used the same model of material aggregation on international material and price search from Alibaba.com as the materials were sold by different suppliers. After aggregating the materials and their prices, minimum, mean, maximum prices and standard deviation for international and local price scenarios were generated. International prices were obtained in United States Dollars (USD) and converted to Ugandan shillings (UGX) using the official middle rate from the Bank of Uganda website as of August 2020 and the same applied when converting local prices to USD. The analysis assessed the average marginal cost that shows the percentage change between the two scenarios in our feasibility study. This justifies the discussion on the entrepreneurial opportunity for biogas socio-technical transition in Uganda.

4. Results

4.1. Case analysis

Biogas technology was first introduced to Uganda in the 1950s by the church missionary society and it has been mostly promoted using a fixed dome digester design (Mwirigi et al., 2014). The technology is mainly promoted using biodigester designs of 8 m^3, 12 m^3 and 16 m^3 capacities. Through public-private partnerships (PPP), a few community, institutional and commercial biodigester plants of about 30 m^3 50 m^3 and 65 m^3 have been operationalised although with limited entrepreneurial capability (Owusu and Banadda, 2017; Walekhwa et al., 2014). Productive estimates from 8 m^3, 12 m^3 and 16 m^3 biodigesters are at US$ 4500, 7000 and 9500 with household financial gains of US$ 2516, 3774 and 5032 respectively and a payback period of less than 14months from each. Developing the use of renewable energy sources like biogas for both small- and large-scale applications is the main policy objective for reducing the energy supply gap in Uganda (MoEaMD, 2019, 2002). The policy objective focuses on large-scale applications, although this has not been implemented.

Uganda has got a variety of biodegradable substrates (feedstock) for biogas production. Substrates currently used for biogas production include animal dung, municipal waste, human excreta, and food remains. Owusu and Banadda (2017) found that animal dung from cattle, pigs, sheep, goats and poultry is the most used substrate by households. From livestock dung alone, biogas can meet 40% of Uganda's primary energy supply with an average potential of 1,300 m^3, equivalent to 7million Mwh and 25.17 PJ of electricity. The Government of Uganda national census 2014, estimated the current livestock population at 73 million cattle, 13 million goats, 14 million sheep, 3 million pigs and 38 million poultry (UBOS, 2014). From these statistics, Uganda can annually produce 1bm^3 of biogas which is approximately 1000Mwh of hydroelectricity. Clemens et al. (2018) found that most of the biogas producing households in Uganda produce excess biogas while others do not produce to full capacity. From this background, the productiveness of biogas energy in Uganda shows a high potential for realising the transition to bioenergy.

4.2. Transitional model canvas for biogas technology in Uganda

4.2.1. Transition goal

The transition goal for this case is "to create a sustainable biogas socio-technical system for large scale applications and wider society consumption and benefit in Uganda". This transition goal is supported

Table 1
Summary of key documents selected and data analysed.

Document selected	Data analysed	TMC analysis
MoEaMD. (2019, 2002). The energy policy for Uganda. Ministry of energy and mineral development (MoEaMD)	The transitional goal, energy policy and energy supply data,	1, 2 and 3
MoEaMD (2015). Uganda's sustainable energy for all (se4all) initiative action agenda. Ministry of Energy and Mineral Development	Transitional goal and policy objectives, biotechnology policy plan	1 and 2
FAO (2018). World Livestock: Transforming the livestock sector through the Sustainable Development Goals.	Livestock statistics in Uganda, bioenergy feedstock and state-of-the-art information on biogas production. Strategies to scale up the existing bioenergy socio-technical system	2 and 3
IRENA (2017). Accelerating the Energy Transition through Innovation.	Energy technology innovations, Recommendations for bottling biogas	2, 3 and 4
Kees, M., & Eije, S. v. (2018). Final Energy Report Uganda. Retrieved from Commissioned by the Netherlands Enterprise Agency:	Biomass energy use data	2
NPA. (2020). Government of Uganda, Third National Development Plan (NDPIII) 2020/21–2024/25.	Energy development plan	1 and 2 Case analysis
The World Bank (2019). Population growth (annual %) Uganda.	Population growth rate and energy distribution	Case analysis
UBOS (2014). National population and housing census.	Livestock statistics for feedstock and household energy access	1,2 and 3
UN General Assembly (2015). Transforming our world: 2030	Explicit analysis of Sustainable development goal 7	3
ERA. (2020). Maximum electricity demand [Statistics].	Energy supply and demand statistics	2 and 3
UNDP (2020). An energy audit experiment to promote renewable energy in large institutions and households.	Current state-of-the-art on renewable energy technologies in Uganda with (biogas usage and satisfaction rate)	3
UBOS (2021). The Uganda National Household Survey Report 2019/2020.	Household energy use	Case analysis

by the deliberations of FAO (2018) which presupposes that Uganda's current energy supply gap could be reduced by bottling biogas for entrepreneurial activities. Besides, the UN General Assembly (2015) Sustainable Development Goal 7 aims at providing affordable, safe and clean energy to a low-income rural and urban population. Similarly, IRENA (2017) found that developing countries need to pursue an agenda that accelerates energy transition through innovations such as bottling biogas for large scale applications.

4.2.2. Existing bioenergy system (incumbent system)

Key elements and interactions. The promotion of biogas technology in Uganda is partly done by the government (Ministry of energy and Environment), non-government organisations (NGOs), and private companies. Some of the NGOs in the initiative include Heifer Project International (HPI), Adventist Relief Agencies (ADRA), American Medical and Research Foundation (AMREF), Schweizerische Normen-Vereinigung (SNV) and Africa 2000 Network (Lwiza et al., 2017; Okello et al., 2013; Walekhwa et al., 2014). The focus for the technology is an energy policy for Uganda-based agenda that presupposes promoting the use of clean affordable renewable energy for small and large scale applications in Uganda (MoEaMD, 2019, 2002). However, implementation is still at an individual household level with service quality and customer satisfaction for single private users. The incumbent socio-technical system is poorly developed to address economic sustainability and/or attract direct income realization for households. Local initiatives aimed at creating productive supply chains are not well coordinated and integrated into the policy framework, even with high biogas production potential in the country. Society is locked in an energy mix,[2] where households use other cheap and easily accessible energy sources like firewood and charcoal. This is coupled with traditional cooking routines, that encourage the use of open fires and inhibit the uptake of biogas.

Strength and vulnerabilities. The current bioenergy socio-technical system is not regulated. Biogas is not the primary energy fuel used by producing households, rather it is used along with other solid biomass fuels that are readily available. However, these fuels are becoming increasingly scarce and more expensive to use due to resource depletion. Any household is free to construct and use biogas and free to exit once they cannot operate the system. Construction of biodigesters is done on private household land, for small scale production and easy management. Digester construction is a free donation from NGOs and government to farming households, who use free feedstock from animal dung as biodegradable substrate (Clemens et al., 2018). The incumbent system faces several vulnerabilities like inefficient R&D, limited knowledge, and expertise for entrepreneurship development (Tumusiime et al., 2019). Additionally, free donation results in inappropriate system handling and once it breaks down, dis-adoption is preferred. For example, Tumusiime et al. (2019) and Lwiza et al. (2017) found that 80 per cent of biogas plants constructed in Uganda are dis-adopted within the first 6years of use, yet they are estimated to last for not less than 25years. Further, the absence of clear regulations for biogas production and management also limits sector monitoring by the state. Therefore, the introduction of entrepreneurial models into the system is likely to create economic gains which could reduce the dis-adoption rate.

Strategies from the incumbent system. These are strategies that are inherent within the existing system that could be used to obstruct the activities of the niche system and prevent it from taking over the supply chain. For example, if current biogas producing households decide to utilize all available feedstock to complement animal dung and share with or sell the bioproducts to non-producing households. When more households in urban areas decide to convert septic tanks into biodigesters, entrepreneurs may have no business. Other strategies according to the model are those that inhibit the niche. For example, households with excess biogas production capacity could start to bottle and sell excess biogas to create productive supply chains and discourage niche start-ups. Therefore, bottling biogas is the focus and main strategy of the niche system and this is articulated in the next section.

4.2.3. Niche system

Focus. The niche system focuses on developing a productive and sustainable model for the biogas socio-technical system through the technological innovation of a mobile biogas purification unit. A mobile purification system is a portable unit that can be moved with the cylinders and assembled on-site to purify, compress and bottle upgraded biogas (Karlsson et al., 2017; Sahota et al., 2018). This system foresees the possibility of bottling biogas by designing a mobile purification system that can be detached for easy transportation and assembled when refilling the cylinders. This working principle is based on two cylinders used with on-off valves to compress the biogas alternately allowing an adjustable operation of the system. The cylinders are connected in parallel, with two valves on each, one controlling flow from the biodigester and another controlling flow of biogas into the cylinder (Kapdi et al., 2005). Ilyas (2006) suggests using a foot compressor to compress the gas into the cylinder. Once the cylinders fill up, compression will

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[2] Households meet their energy needs by using different types of energy available to them in differing proportions. In Uganda, households use a mixture of firewood, charcoal, LPG gas, electricity, and kerosene (UBOS, 2021).

become difficult then they can be disengaged to connect others. The purified gas is produced after a chemical absorption and adsorption purification process which removes carbon dioxide (CO_2), hydrogen sulphide (H_2S) and water vapour (H_2O) to increase the percentage of methane from 60% to about 98%. Different upgrading mixtures are recommended for the purification process. Nevertheless, in this study, a mixture of calcium oxide (CaO), activated carbon and sodium sulphide (Na_2SO_4) is preferable, following the works of Al Mamun and Torii (2017). After purification, the output gas becomes biomethane. Biomethane is could then be compressed into the cylinder using a foot compressor that aims to reach a high-pressure gas storage system through a pressure vessel delivering a minimum of 0.015 m^3/min and up to 150 bar pressure (FAO, 2018; Ilyas, 2006; Kapdi et al., 2005; Pramanik et al., 2019; Ray et al., 2016)

Key elements and interactions. The entrepreneurs build and drive the niche system, they are also responsible for developing the biogas upgrading technology (mobile purification unit) and building relationships and linkages for a successful transition process. Other parties that may join the chain include non-biogas producing households (customers), feedstock suppliers, new entrants (entrepreneurs and producers as competitors). Upgrading and bottling biogas after purification is likely to increase energy supply especially in rural areas and may probably solve the rural electrification challenge by creating economies of scale.

Strength, vulnerabilities, and uncertainties. The niche system relies on several factors to reinforce its development and these include the following: High levels of limited energy access, increasing scarcity of wood fuel, increasing charcoal and firewood prices, low-cost, and availability of resources locally to develop the purification technology, and ability of biogas energy innovations to mitigate climate change. Additionally, an increase in biogas uptake can reduce over-reliance on hydroelectricity, the slurry from biogas can reduce the use of pesticides and improve agricultural yields. Nevertheless, the system is vulnerable to traditional cooking routines that encourage the use of solid fuels as the primary source of energy, limited capabilities for sector development, lack of role models to benchmark from, and competition from liquified petroleum gas (LPG) which is already on the market. The niche system also envisages some uncertainties like low acceptability and profitability of the venture.

Strategies in the niche system. Containerization of biogas is the main strategy for destabilizing the incumbent system. This could further be supported by the government regulating tree cutting and heavily taxing charcoal and firewood fuels, which compete with and are often preferred to biogas. Institutions could also limit the free of cost biomass promotion strategy to encourage entrepreneurial activities in the sector. To strengthen the niche, the government could train youths to take the lead in the sector for employment. The government could also subsidize biogas entrepreneurship, legalize the sector for quality assurance and give it the same priority as hydropower production.

Strategic resources. Most of the strategic resources needed for a successful transition to biogas energy are locally available in Uganda. What is missing is the lack of technical data to support biogas generation from the biomass resources available (Tumusiime et al., 2019). Similarly, policy support on renewable energy development emphasizes small-and large-scale applications although, it is not clear on energy business development like the one studied in this paper. There is also limited technical knowledge and expertise on how to develop the purification system, which is likely to cause delays in realising the transition to bioenergy. Besides, there is limited knowledge on the exact materials and their costs required for developing the mobile purification unit.

Feasibility analysis. Findings from key informant interviews with biomass entrepreneurs indicate that world market prices for developing biodigester and purification units exceed willingness to pay among potential Ugandan customers and would-be entrepreneurs. This finding is in line with the findings of Kabyanga et al. (2018). A crucial assumption in these findings is that there is no local value chain that could produce and market mobile biogas purification systems at lower shipping and labour costs. However, the findings from the feasibility study presented in Fig. 2 and Appendix 1 indicate that prices have fallen somewhat, and material availability has increased locally. An assessment of how much the total costs can be reduced under the scenario of local production is presented by a comparison of the average marginal costs in Fig. 2 using data from Alibaba.com. Distributions of marginal unit cost items and totals are displayed in Appendix 1, Table 3 (for the scenario that all components are imported) and Table 4 (for the scenario that all components are locally sourced).

Fig. 2 (and Table 3 in Appendix 1) show that in the scenario that materials are imported, the entrepreneur will pay for the component cost of $866, shipping costs of $133 and import tax of $2244 for a single purification unit which makes the proposed technology very expansive to consider. Whereas in Scenario 2 (Table 4 in Appendix 1), where materials are sourced locally, the entrepreneur will not need to pay shipping and tax costs except for transportation during aggregation of the components and to the construction site. Construction is a fixed cost in both scenarios, and the assumption is that construction is made in Kampala, which is the central district, where all materials are sold and easily accessible. Once one moves away from Kampala, the construction and transportation costs may change based on the location or construction site. If all components are sourced locally, a marginal cost reduction of 64% is obtained as shown in Fig. 2. Compared to Scenario 1, the cost of the purification unit in Scenario 2 is relatively low. Thus, Scenario 2 presents a high likelihood of local investment into biogas entrepreneurial supply chains.

4.2.4. Landscape

The socio-technical landscape consists of infrastructure that creates pressure on the niche system. Factors like the free collection of firewood in rural areas, cooking cultures and traditions that encourage the use of open fires (3-stone) and energy mix affect consumers decision making to change to biogas consumption.

5. Discussion

The TMC model presented in Fig. 1 shows that the biogas social-technical system comprises a niche that energy entrepreneurs could exploit using entrepreneurial business model approaches. This implies that actors with entrepreneurial intentions are expected to jump into the system, seize business opportunities and create productive energy supply chains which will lead to realising the transition to bioenergy. The model further reveals that policies and institutional demands are potentially important drivers for entrepreneurship and innovation in the energy sector. This is because the energy policy encourages innovations geared towards increasing the energy supply. However (Lwiza et al., 2017), found that there is institutional lethargy in the monitoring and following up on energy policy impacts and implementations which may cause delays in the transition process. Nevertheless, institutional support could go a long way to offer subsidization of upgrading materials, provision of low-interest loans, or tax holidays. This could encourage energy business growth, create competition among actors and/or encourage collaboration, for speedy transitions.

The TMC also reveals several strengths and vulnerabilities that are likely to influence the success of the niche system. The identified strengths are likely to enable the creation of repeatable and scalable entrepreneurial processes to encourage competitive supply chains in the biogas socio-technical system. The vulnerabilities on the other hand reveal that the niche system is unstable. The system has got both internal factors (limited dynamic capabilities in the sector, lack of technical data to support the production of biogas at a large scale and limited sector role models) and external factors (Limited policy attention targeted towards biogas production, competition from other cheap energy sources like firewood and LPG, strong traditional cooking routines that encourage the use of firewood) that destabilize the niche system. This

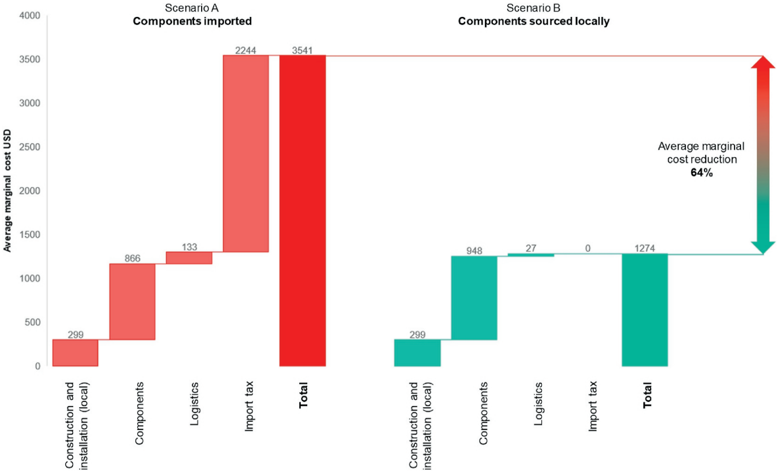

Fig. 2. Comparison of the average marginal costs (USD) between scenarios with the import of components versus local sourcing of components.

implies that system builders may need to develop dynamic capabilities that will help them to convert vulnerabilities into opportunities. This will also enable them to productively change existing practices or resource configurations, show their willingness to undertake change, and their ability to implement such change to overtake the incumbent system. Dynamic capabilities relate to the entrepreneur's ability to reconfigure resources and practices in a planned and appropriate manner that enables firms to pursue opportunities in new and potentially effective ways (Zahra et al., 2006).

The model further shows uncertainties that could come with this venture creation. For example, in the TMC for biogas in Uganda, there is uncertainty as to whether the targeted market will consume the containerised gas. There are also no established findings to show that the proposed venture will be profitable or that customers will be willing to consume bioproducts as the model presupposes. However, such findings are beyond the scope of this paper and future researchers in this area could explore them. Whilst the model identified vulnerabilities and uncertainties that are likely to antagonize the niche system, it also found some strategies to destabilize the incumbent and strengthen the niche systems respectively. Destabilizing the incumbent implies that government and private stakeholders promoting biogas abandon the free of cost and free of service model to allow the birth of productive value chains. This also implies that the state could subsidize biogas purification and bottling ventures so that it is availed to consumers at a low cost to attract increased uptake. To strengthen the niche system, the model found that capacity building is vital, and this can be done by training youths to take the lead in the entrepreneurial process. The significance of this strategy is to reduce youth unemployment. The strategy of legalising and regulating the sector on the other hand have implications for increased service value and quality assurance of bioenergy to society.

The analysis of findings further reveals that several resources are available and accessible in-country to enable commercialisation of biogas (e.g., online scientific materials, low-cost materials locally to build the purification unit, funding for clean energy innovations and renewable energy campaigns) but the incumbent system has not fully exploited them. Nevertheless, there are also missing resources like lack of technical data to support biogas generation from the biomass resources available and lack of a clear policy to support biogas energy commercial ventures. The niche system could thus employ the available strategic resources to destabilize the incumbent system while strengthening the niche activities, but also use the missing resources as an opportunity to lobby for policy support. Finally, for the proposed entrepreneurial model, a comparison of local and international scenario market survey in the feasibility study indicates that the materials to build the purification unit are locally available at a low cost. This signifies that investing in purifying and bottling biogas as a clean fuel is doable and that the transition to bioenergy in Uganda is achievable. This transition could be realised through integrating entrepreneurial business models into the biogas social-technical system. Finally, the findings from the qualitative interviews and document analysis reveal that system builders and other stakeholders may have to perform several activities in the process of transitioning for society to benefit from the proposed technology. Some of these activities are abridged in Table 2.

5.1. *Limitations and future research*

Despite making a rigorous examination of several kinds of literature and practical qualitative assessments to complete this study, the authors identified some limitations. First, there is limited technical data in Uganda's archives to support biogas generation studies and upgrading from the biomass resources available. Second, the materials for building a purification unit are not sold by a single supplier, thus, the feasibility required aggregating components from several suppliers which become tedious and time-consuming since suppliers are not concentrated in one place. Third, the proposed technology has not received concentrated institutional support despite its paramount role to relieve the country of its energy supply burden. Future research on biogas entrepreneurship should identify how these limitations could be resolved. Scholars need to assess the role and willingness of the state to promote productive biogas supply chains. Particularly, scholars could also investigate and assess the economic viability or profitability of the proposed entrepreneurial model. Research on the willingness of consumers to pay for and use biogas as a primary energy source would also be vital for reducing consumer rejection of this energy source.

6. Conclusions and recommendations

To conclude, this article has aimed to assess the entrepreneurial

Table 2

A summary of actors, activities, and benefits of the niche system.

Actor	Activity	Benefits
Institutions • Government • NGO • Financial institutions	Provide enabling environment (regulatory and policy framework, fair tariffs) Provide subsidies Fund biodigester construction Dissemination and scale-up of biodigesters Training biodigester engineers and masons Sensitization, demonstration, and provision of information Provide loans for construction of anaerobic digesters Provide loans for entrepreneurial start-ups	Encourages new entrepreneurial activity Increased energy access Reduced emissions Reduced unemployment Source of Knowledge through training Increase scale-up and uptake of biogas technology The reduced financial burden for Construction and business start-up
Material supplier	Stocks and sell biodigester construction materials Stocks and sells biogas appliances (stoves, piping, valves, lamps) Stocks and supplies digester spare parts Stocks and supply purification and compression materials Looks out for and provides new technology of materials	Makes materials locally available for easy accessibility to producers
Engineers and masons	Construction of biodigesters services Advice and guide farmers on-site location digester design and capacity Advice on materials and quantities for better quality Training farmers on the operation of digestors	Available for maintenance Employment
Households • Farmers	Aggregate's construction materials Aggregate's residues and feedstock for anaerobic digestion Makes construction decisions The operation, management, and maintenance of the biodigester to produce gas and slurry Gathering wood for cooking	The reduced wood collection time New farming activities using bio-slurry Increased household incomes through selling excess biogas and slurry Diversification into energy supply to supplement food incomes Source of new employment
Entrepreneurs (System builders)	Focal point enterprise Channel of delivery to a wider market Source of information to and from external market The link between producers and market Containerizing/bottling and aggregation gas from farmers Developing the bottling system Extending the current model (responsible for transition activities) Biogas Pricing Networking Visioning Identify new producers to increase supply	Commercializing and popularizing the use of biogas energy Automatic scaling up and increased uptake of biogas energy New employment opportunities created Increased awareness of biogas technology Main agent for the transition process Increased Energy supply Reduce deforestation
Customers • Non-digester owning households • Fuel stations	Purchase and use bottled biogas Purchase and use slurry Purchase and resale bottled biogas Promote biogas use in transportation and industry	Increased uptake reduces emissions Reduced cooking time Reduced violence on women and girls Reduced emissions
Feedstock supplier (Off-farm)	Aggregate's feedstock to supply to Digester owners	Source of employment
New entrants • Imitators • Producers • Competitors (LPG sellers)	Buy and sell biogas from households May construct new biodigesters Create a competitive environment in the existing market Scaleup and increase uptake of bioproducts	Reduce consumption of black carbon fuels Reduced emissions Increased employment Economic growth Increased energy supply

opportunity and feasibility of purifying and bottling biogas into portable cylinders for wider social consumption in Uganda. The article analysed this possibility using a transitional model canvas created using the multi-level perspective and business model innovation frameworks, and a feasibility assessment of the key resources needed to purify and bottle biogas in portable cylinders. Whilst the multi-level perspective comprehensively explains the process of change, the business model innovation framework helps to enable the process of enacting the suggested change processes in socio-technical systems transitions. Our findings indicate that integrating entrepreneurial business models into the biogas socio-technical system in Uganda is achievable and affordable. Second, developing productive biogas supply chains would increase wide society access to clean and affordable energy thus contributing to sustainable development goal 7. Third, the study contributes to solving a real-world problem through action research methods and shows how scientific knowledge can be used to solve social challenges. Fourth, combining the MLP and BMI frameworks into the TMC provides a clear and succinct structure for analysing and enacting socio-technical systems transition relating to society functions. Using the concepts from these frameworks enables a simple analysis, easy dissemination and display of empirical findings relating to the delivery of societal functions and creation of innovations that lead to radical change.

Finally, the study insights revealed some recommendations. First, this innovation option can be practically explored by entrepreneurs in the clean energy sector and energy funding should be directed to such developments. Second, the government, NGOs, and the private sector promoting biogas energy use should adopt such an entrepreneurial model to promote productive supply chains beyond private households. Third, the energy policy for Uganda should encourage the growth of energy businesses through entrepreneurship development and innovation approaches. Such entrepreneurial energy businesses should be subsidized, and the public should be sensitized to take up such clean energy sources. This is likely to not only increase energy supply but also promote other sectors of the economy like agriculture which consumes the slurry and promote the dignity of women who are involved in the cooking activities especially in the rural areas. It will also aid in conserving the environment, reducing indoor air pollution and emissions through reduced tree cutting, lessening the use of solid biomass fuels and open fire cooking respectively.

CRediT authorship contribution statement

Irene Namugenyi: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Lars Coenen:** Conceptualization, Formal analysis. **Joachim Scholderer:** Conceptualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the NORAD/NOHED project for funding this work, the editor and the anonymous reviewers for the valuable and insightful comments on earlier drafts of this manuscript.

Appendix 1

Table 3
Distribution of marginal unit cost items and totals under the scenario that all components are imported (for each cost item, four different price quotes were solicited from separate vendors/contractors)

Component	Price USD				Price 1000 UGX			
	Min	Mean	Max	SD	Min	Mean	Max	SD
Calcium oxide (1 kg)	6.30	7.90	10.00	1.89	23.16	29.04	36.76	6.96
Compressor/pressure pump (1 unit)	47.00	70.25	100.00	22.02	172.77	258.24	367.60	80.95
Cylinder cover plates (1 unit)	6.00	8.50	10.00	1.73	22.06	31.25	36.76	6.37
Gas control valve (1 unit)	3.00	14.28	30.00	13.05	11.03	52.47	110.28	47.96
Gas cylinder (1-unit à 13 kg)	17.00	19.00	23.00	2.71	62.49	69.84	84.55	9.95
Gas flow meter (1 unit)	260.00	381.75	498.00	119.21	955.76	1403.31	1830.65	438.21
Hose pipe (1 roll)	20.00	35.00	50.00	12.91	73.52	128.66	183.80	47.46
Iron oxide (1 kg)	1.25	2.00	2.50	0.56	4.60	7.35	9.19	2.06
Non-return valve (1 unit)	4.00	36.00	70.00	27.28	14.70	132.34	257.32	100.27
Piston, rings, and rod (1 set)	13.00	25.73	50.00	17.00	47.79	94.57	183.80	62.49
Plastic hose pipe (1 roll)	22.00	55.50	84.00	31.17	80.87	204.02	308.78	114.59
Pressure gauge and male connector (1 set)	3.50	100.13	228.00	93.52	12.87	368.06	838.13	343.77
Quick exhaust valve (1 unit)	10.00	12.75	16.00	3.20	36.76	46.87	58.82	11.77
Safety valve (1 unit)	1.50	6.38	14.00	5.88	5.51	23.43	51.46	21.61
Solenoid valve (1 unit)	39.00	59.75	90.00	21.91	143.36	219.64	330.84	80.56
Silica gel (1 kg)	1.50	2.60	3.00	0.73	5.51	9.56	11.03	2.70
Silicon (1 piece)	0.80	1.03	1.50	0.33	2.94	3.79	5.51	1.20
Steel wire mesh (6 kg)	0.40	1.00	2.00	0.71	1.47	3.68	7.35	2.62
Sodium sulphide (1 kg)	10.00	26.25	45.00	18.87	36.76	96.50	165.42	69.38
Shipping/logistics	109.00	132.50	163.00	23.13	400.00	487.50	600.00	85.39
Import tax payable	1632.00	2244.00	2720.00	464.53	6000.00	8250.00	10000.00	1707.83
Total component cost	2207.25	3242.28	4210.00		8113.94	11920.11	15478.05	
Construction and installation (local)	244.73	299.11	353.50	49.65	900.00	1100.00	1300.00	182.57
Total marginal unit cost	2451.98	3541.39	4563.50		9013.94	13020.11	16778.05	

Note: 1 USD is equivalent to 3677.53 Ugandan shillings (UGX).

Table 4
Distribution of marginal unit cost items and totals under the scenario that all components are locally sourced in Uganda (for each cost item, four different price quotes were solicited from separate vendors/contractors)

Cost item	Price USD				Price 1000 UGX			
	Min	Mean	Max	SD	Min	Mean	Max	SD
Calcium oxide (1 kg)	19.03	25.83	38.07	8.45	70.00	95.00	140.00	31.09
Compressor/pressure pump (1 unit)	188.17	215.97	240.65	24.20	692.00	794.25	885.00	88.99
Cylinder cover plates (1 unit)	39.43	42.15	43.51	1.92	145.00	155.00	160.00	7.07
Gas control valve (1 unit)	65.26	67.64	69.34	1.71	240.00	248.75	255.00	6.29
Gas cylinder (1 unit à 13 kg)	35.35	38.00	40.79	2.22	130.00	139.75	150.00	8.18
Gas flow meter (1 unit)	54.38	61.18	65.26	5.21	200.00	225.00	240.00	19.15
Hosepipe (1 roll)	59.82	64.24	70.70	4.89	220.00	236.25	260.00	17.97
Iron oxide (1 kg)	19.03	23.79	29.91	4.64	70.00	87.50	110.00	17.08
Non-return valve (1 unit)	19.03	21.21	25.56	2.98	70.00	78.00	94.00	10.95
Piston, rings and rod (1 set)	70.70	72.06	73.42	1.11	260.00	265.00	270.00	4.08
Plastic hose pipe (1 roll)	11.42	13.73	16.32	2.00	42.00	50.50	60.00	7.37
Pressure gauge and male connector (1 set)	78.31	78.72	78.86	0.27	288.00	289.50	290.00	1.00
Quick exhaust valve (1 unit)	29.91	32.63	38.07	3.85	110.00	120.00	140.00	14.14
Safety valve (1 unit)	27.19	30.59	32.63	2.60	100.00	112.50	120.00	9.57
Selenoid valve (1 unit)	48.95	55.06	62.54	5.61	180.00	202.50	230.00	20.62
Silica gel (1 kg)	19.03	28.89	33.99	6.79	70.00	106.25	125.00	24.96
Silicon (1 piece)	3.26	3.47	4.08	0.41	12.00	12.75	15.00	1.50
Steel wire mesh (1 roll à 6 kg)	16.32	21.14	32.63	7.76	60.00	77.75	120.00	28.52
Sodium sulphide (1 kg)	19.58	24.27	32.63	5.97	72.00	89.25	120.00	21.96
Local transportation/logistics	27.19	27.19	27.19	0.00	100.00	100.00	100.00	0.00
Total component cost	851.39	947.78	1056.14		3131.00	3485.50	3884.00	
Construction and installation (local)	244.73	299.11	353.50	49.65	900.00	1100.00	1300.00	182.57
Total marginal unit cost	1096.12	1246.90	1409.64		4031.00	4585.50	5184.00	

Appendix 2

Woman in Luwero district cooking inside a kitchen with black wall from an accumulation of soot.

Appendix 3

Questions for the key informant interviews.

As a biomass technology entrepreneur (or head of this institution) we would like to seek for your knowledge on the general use of biomass resources and technologies. We therefore request for your time to respond to the following questions (This interaction should be recorded, ask for permission to record the session)

1. Biomass and the environment
    1. Where do you buy your firewood/charcoal?
    2. Do you know where your suppliers get the fuel from?
    3. What is your feeling about people who cook on open fires?
    4. Have you ever talked to your suppliers about how easy it is to find you firewood, what was their response?
    5. Do you have any knowledge on the environmental impact of the fuel source you use?
    6. Are you concerned of the environmental effects of the fuel source you use?
2. Biomass and ICS
    7. When was the first time you wished that there would be better cookstove technology than the traditional stoves?
    8. Was this related to a particular experience with the cookstove you had then? Can you describe the experience?
    9. Do you think the idea of adopting to improved cook stoves is important for this country?
    10. Where and when did you learn how to use a stove for professional cooking? - what was it like on the normal stove before the considered the improved one
    11. How did you first hear about the improved cookstoves? – consideration phase before they considered improved cookstoves.
    12. Was there a particular colleague/supplier/sales agent/customer/friend who first told you about it?
    13. Try to remember what she or he told you. What was it about the new stoves that made you interested?
    14. How did you first hear where you could buy such stoves?
    15. Did you only hear about one supplier or several?
    16. How did you finally get into contact with the first supplier? Was it you who initiated the contact, was it the supplier, or somebody else?
3. Other Technologies (How might we help rural households find better cooking options that will improve their general quality of life)- For biomass Entrepreneurs and school head teachers
    17. Do you know of any other energy efficient technologies that households or schools could adopt to reduce biomass use?
    18. Have you used or seen anyone using those technologies?

19. Have you tried making/thought of making such technologies before?
20. If yes, what inspired you to make them. If no, why haven't you made or used them?
21. What was your feeling when you used/saw someone using those technologies?
22. Are you still using/making those technologies?
23. From the technologies you have used, made or seen somewhere, which one do you think could be the best to use by todays households and why?
24. For those you have seen/use/made, which ones have the households appreciated more and why?

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Paper IV

Valorization of biogas for market development and remission of “environmental nuisance” in Uganda

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Highlights

- The methane quality of biogas in Uganda is still low to stand a chance in the market
- Small-scale producers cannot sell biogas, they thus release it, causing global warming
- Customer segments for biogas are bioenergy entrepreneurs, gas companies and electricity suppliers
- Valorization technologies and strategies are needed to improve the quality of biogas in Uganda.

Abstract

In Uganda, biogas is a low-value product considered a pro-poor renewable energy source. Farmers with excess biogas release it into the atmosphere contributing to global warming. This study used mixed data sources and methods to explore how biogas can be valorised to stand a chance as a commercial market offering and reduce greenhouse gas emissions. The results reveal that the biogas produced in Uganda does not meet the desired 98% methane quality to stand a chance as a commercial market offering; the pilot production process never got close to even the lower specification level of 95% for upgraded methane (CH_4) and the upper specification level of 5% for carbon dioxide (CO_2). The study also found that small-scale biogas producers with excess gas have a high desire to sell it but have no idea of how to valorize it to reach the market. Thus, they end up releasing these greenhouse gases. Furthermore, clear clustering of the product category, bioelectricity/biogas, reveals three promising customer segments: bioenergy entrepreneurs, gas companies and electricity suppliers. These results imply that to become a commercial market offering, the quality of biogas needs to be improved using valorisation strategies like monitoring gas quality, shaping the market, market research and certification and controls. The bioenergy policy could consider subsidizing valorisation technologies to make them affordable for farmers and thus support a more climate-smart biogas business development.

Keywords: Valorisation, market development, biogas production; sustainable production; “environmental nuisance”; Uganda

1. Introduction

The global desire for sustainable development coupled with the need to increase access to clean energy and reduce emissions has increasingly led to the production, application, and use of biogas at a commercial level. (Lal SR et al., 2022). Biogas production is a versatile business with one service and two products; the service is waste management, and the products are biogas and digestate. In developed countries like Sweden, Germany, The Netherlands, Denmark, and the United Kingdom, biogas has become a high-value product used as an alternative to natural gas in transport and industry (Lindfors et al., 2020). The digestate from biogas is a highly valued organic fertilizer used as an alternative to mineral fertilizer in improving soil nutrients and increasing agricultural yields. Because of this versatility, biogas is considered one of the most sought-after renewable energy sources across the world to overcome the clean energy challenges and food insecurity faced by today's society (Aravani et al., 2022). However, in the case of Uganda, biogas is still a low-value product considered a pro-poor renewable energy source (Bluemling et al., 2013; Clemens et al., 2018). Biogas in Uganda is produced and consumed at a small scale by private livestock farming households and public research institutions like the National Agricultural Research Organization (NARO). Nevertheless, Bluemling et al. (2013) states that some biogas producers have excess capacity which they are unable to consume. Because the excess capacity causes pressure build-up, that can burst the digesters, it is often and intentionally released into the atmosphere. The act of releasing the gas into the atmosphere is an "environmental nuisance" that undermines the demands from the climate agenda of the world transition towards a biobased emission-free society.

The biogas released into the atmosphere contains methane which has a 25 times higher impact on climate than CO_2. In other words, the methane global warming potential is 25 times stronger than one CO_2 molecule (Beil & Beyrich, 2013; Khan et al., 2021). While biogas is being released to damage the environment, it should be noted, that it is the only available gas from renewable sources, and the only versatile energy source with numerous applications in the household (cooking and lighting) domestic, and transportation industry. That said, Uganda's transport system heavily depends on fossil fuels and its largest population (about 85%) relies on solid biomass (firewood and charcoal) and kerosene to meet their energy needs (Elahi, 2019; UBOS, 2021; UNDP, 2020). The heavy dependency on the solid biomass has caused depletion of forest resources and thus calls for a transition into the liquid bioenergy alternatives like biogas. However, Namugenyi et al. (2022), assert that biogas production in Uganda is still underdeveloped and not mature enough to stand a chance as a commercial market offering. However, when converted to biomethane, biogas is valorized and can substitute natural gas, reduce the consumption of fossils and the energy supply gap, as well as provide clean energy to society (Karlsson et al., 2017). The question at this point is how such a high-quality energy carrier like biogas be valorised to stand a chance as a commercial market offering instead of wasting it by releasing it into the atmosphere, adding to global warming, when so many households in Uganda lack access to clean energy and the transport system is highly dependent on imported non-renewable fossil fuels. According to Zhang (2022) discussions concerning this question are critical today, and not in the distant uncertain future. Scholars like Beil and Beyrich (2013), Lindfors et al. (2019) and Offermann et al. (2011) envision biogas as the fuel of the future, thus valorising it today will change the future power supply market conditions, particularly for clean energy, in a positive manner. Therefore, there is an urgent need for the valorisation of biogas for market development. Valorisation and market development will help to reduce the uncontrolled release of biogas into the atmosphere and enable its integration into the future sustainable energy supply in Uganda.

To valorize is to enhance or try to enhance the price, value, and status of a product by organized and usually governmental action[1]. For instance, the government can use subsidies to valorize biogas such as investing in new upgrading technologies. Valorizing biogas is a complex process that starts with choosing the right feedstock to give quality raw biogas, upgrading the raw biogas to biomethane and digestate management (Wellinger et al., 2013). Each of the stages requires high-level process knowledge with significant investment and involvement of different actors from the state and private sector to support, develop technologies, launch products, and shape markets, regimes, and controls; from which a valorized commercial biogas product can be offered to the market.

From the production stage, biogas leaves the digester saturated with methane (CH_4), carbon dioxide (CO_2) and other impurities. Depending on the feedstock (substrate) used, the CH_4 content in the raw biogas fluctuates between 40% to 75%, carbon dioxide is 25% to 50% and water vapor

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[1] https://dictionary.cambridge.org/dictionary/english/valorize

(H_2O), hydrogen sulphide (H_2S) traces and oxygen (O_2) range between 2% and 8% (Hagos et al., 2017; Pramanik et al., 2019). The methane content in biogas is the main component of interest for energy production, commercialization, supply, and use (Aryal et al., 2021). Therefore, in commercial biogas production, the main aim is to ensure that as much methane as possible is produced by anaerobic digestion from the available substrates. Whilst raw biogas is used for cooking, its H_2S impurities are toxic to human health. The gas may also not be used for large-scale applications like motor vehicle fueling because it contains impurities like water and H_2S that may corrode gas engines. For such applications, the raw biogas should be valorized and/or upgraded to biomethane by removing carbon dioxide and other impurities (Kapoor et al., 2020).

Cleaning and upgrading biogas to biomethane is by far the most common biogas valorization strategy. Cleaning raw biogas refers to the separation of undesired gas compounds like H_2S and water while upgrading refers to the separation of carbon dioxide (CO_2) from methane by purification (Aryal et al., 2021; Kapoor et al., 2020). In the purification process, CO_2 is reduced, and the methane content increases to about 98%, which gives biogas the same properties as natural gas (Al Mamun & Torii, 2017). According to Fallde and Eklund (2015) and Sahota et al. (2018), the high methane property in biogas allows for its applicability in all systems that natural gas can be applied to. Furthermore, valorized biogas can be stored using the same infrastructure as natural gas in mobile cylinders for future use and easy movement to the market. This characteristic makes biogas the only renewable source with high energy efficiency, flexibility, versatility, and storability. These characteristics give biogas the advantage of being affordable, clean, safe, and sustainable, and places it as an important contributor to sustainable renewable energy supply (Khan et al., 2021).

Kapoor et al. (2020) assert that the valorization of biogas is an important driver for market development and increased investment in the biogas industry. However, to valorize biogas, and take benefit from its efficiency and versatility, Uganda has a considerable catching up to do in terms of its bioenergy policies. The bioenergy policy may need to press ahead with positive public relations to improve public acceptance (shaping the market) by communicating the positive role of biogas in the future sustainable energy supply (Rupf et al., 2016). In line with this point, FAO (2018) and Clemens et al. (2018) found that the promotional and or market value of biogas in Uganda has been underestimated; yet, it has a high potential to enable individuals and households live in a clean and sustainable society, enable producers to obtain productive applications for biogas in ways that create tangible and monetary value for individuals, households, and the wider society; and enable biogas integration into the future sustainable energy supply in Uganda. For this reason, *the purpose of this paper is to explore how biogas can be valorised to stand a chance as a commercial market offering and reduce "environmental nuisances" in Uganda.* To fulfil this purpose, this study uses a mixed method (Croswell, 2011; Maxwell, 2012) that includes case study analysis, semi-structured interviews, pilot production (actual measurement and monitoring of biogas quality), and stakeholder analysis survey. These methods were used to study the biogas system at the NALIRRI zero waste plant in Uganda. Other methods included observation and stakeholder (customers and farmers) analysis. Taken together, the data sources and methods were used to corroborate the findings from the different sources. The methods were also used alongside insights from the market development and sustainability transition theories (Pansera & Sarkar, 2016).

The methods used in this study produce findings that empirically contribute to action-oriented mechanisms of generating demand for energy that is cleaner than energy from conventional sources. The findings also build on literature addressing limited access to clean, affordable, and sustainable energy for all (MoEaMD, 2015; UN General Assembly, 2015 7.a, 7.b), reducing emissions and mitigating climate change (Mazorra et al., 2020). Furthermore, this article contributes ideas to the renewable energy policy, particularly on how to reduce the energy supply gap through valorization and integration of biogas into the renewable energy mix in Uganda. The rest of the paper is organized as follows. Section 2 presents the state of market development for biogas in Uganda. Section 3 conceptualises drivers for the valorisation of biogas for market development, Section 4 explains the materials and methods used to investigate the findings of the study, Section 5 presents the results and discussion with limitations, and areas for future research and section 6 provides the conclusions and recommendations.

2. Market development for biogas in Uganda

Uganda's renewable energy policy strategizes to develop the liquid bioenergy market by providing incentives for private sector investment into producing biomethane as a substitute for natural gas and clean energy for underserved communities (MoEaMD, 2007; WWF, 2015). Following this policy strategy, the government of Uganda together with development partners have promoted biogas technology in livestock-keeping households under zero-grazing systems, (Clemens et al., 2018; Namugenyi et al., 2022) to a tune of 9500 active biodigester plants (UBOS, 2021). More to that, in 2017, the government of Uganda funded the construction of a 116m^3 production capacity plant at the National Livestock Resources Research Institute (NaLIRRI) in Nakyesasa in Wakiso district. A similar plant was constructed at the National water and sewerage cooperation facility in Bugolobi, Kampala district. The Bugolobi plant is currently closed due to technical issues but before closure, it was one of those that would produce excess biogas capacity and release it into the atmosphere. The plant at NaLIRRI is currently the largest in Uganda with a production capacity of 116m^3 (approximately 16000L) of raw biogas per day. NaLIRRI is equipped with technology that purifies the raw biogas to biomethane. The institute's main aim is to upgrade and package the gas into mobile cylinders for business development. However, this goal has not been achieved due to limited know-how of purification processes and a lack of packaging technology.

The small-scale biogas producers on the other hand use the gas in its raw form to meet their domestic energy needs like cooking and lighting. However, previous research shows that the amount that is used in households is often less than the amount produced in the digesters, which causes its uncontrolled release into the atmosphere (Bluemling et al., 2013). Whilst biogas is being wasted, the demand for power in Uganda is very high to be met by other fuel sources like hydroelectricity and solar (Kees & Eije, 2018; UBOS, 2021). Moreover, the choice of potential substrates to produce biogas is as versatile as its applications and ranges from animal manure to farm residues and energy plants (IRENA, 2017). This vast number of substrates, however, requires process optimization and shaping the market to create demand for biogas in Uganda. Clemens et al. (2018) contend that the biggest barrier to sustainable biogas production in Uganda lies in the failure of the national government to initiate and implement policies that support the continued processing of the available substrates for domestic biogas production. A valorisation for market development approach focused on increased production of biogas could thus be a potential solution to initiate better policies aimed at enhancing biogas production in Uganda.

3. Biogas valorisation and market development

A major aim for valorising biogas in Uganda is to make it a commercial market offering and reduce global warming caused by the release of greenhouse gasses into the atmosphere. The concept of market development refers to introducing a product or solution with a value proposition to an audience that has not been served or to new uses and applications (Chidanand et al., 2021; Pansera & Sarkar, 2016). Valorisation of social-technical systems like biogas is driven by several factors and/or strategies targeted towards identifying and shaping markets for green products (Ottosson et al., 2020). Once the product is valorised, its public acceptance and customer value creation are also enhanced. Following the objective of this paper, we discuss and empirically investigate some valorisation strategies that might be important drivers for market development and remission of "environmental nuisances" in Uganda.

Monitoring the quality of biogas

The inputs and outputs of biogas production need to be standardized to achieve quality and sustainability for value creation and revenue potential (Aravani et al., 2022). Additionally, to create a higher degree of control over what comes in and out of the digester, it is important to know enough about the feedstock quality and operation of the entire biogas system, and the factors that influence them (Koenig & Dehn, 2016). Characterizing and analysing feedstocks helps to determine their methane potential and revenue forecasts. The feedstock quality and digester volume determine the methane quality and quantity of biogas and has a direct impact on the overall economics of the system; the main interest for operators is to maximise methane volumes because it's the valuable product of monetary exchange (Pramanik et al., 2019). Wellinger et al. (2013) found that sometimes feedstock might accidentally be supplied to the digester with various unwanted components like sand, soil, plastic, and metal and this can cause perturbations in normal operations. This can cause sedimentation on the bottom of the digester leading to reductions of its active volume; other challenges can be process failure through foaming, phase separation, scum, floating layers or even damage to machinery such as pumps caused by metallic impurities and other disturbing components. Therefore, the quality of the feedstock entering the digester must be monitored and observed since it has a high impact on the methane yield in biogas and can affect biogas revenues (Koenig & Dehn, 2016).

To observe the purity of the gas, the raw and upgraded biogas is monitored. Namugenyi et al. (2022) discuss the process of upgrading biogas for market development. The process valorises the gas into biomethane which can be used as a motor vehicle fuel in engines designed for compressed natural gas (CNG) (Ray et al., 2016). However, to be used as a vehicle fuel, the percentage of methane in the gas must be higher than 70% to avoid engine knock. When raw biogas is used to fuel equipment and machinery, it may increase the maintenance requirements and reduce the life span of the equipment to which it is applied (Wellinger et al., 2013). Valorising biogas opens it up to wider market applications, like electricity production, cooking and lighting in non-producing households and industrial processes.

In the process of upgrading biogas, H_2S is a big concern because of its corrosiveness to equipment, odour, and toxicity to humans (Wellinger et al., 2013). Cleaning H_2S from the raw biogas before upgrading it to biomethane is thus a process optimization parameter and a health remedy (Koenig & Dehn, 2016). When biogas is combusted before cleaning, H_2S is converted into sulphur oxides which react with water to form sulphuric acid (H_2SO_4). Sulphuric acid corrodes metallic components and acidifies engine oils. Similarly, Aryal et al. (2021) asserts that to avoid trouble in operation, damaging the energy conversion process and causing catalytic converter poisoning, the residual H_2S in upgraded biogas should be less than 20PPMv (0.002%) especially if it is to be used as vehicle fuel. Removing H_2S and water is followed by the separation of CO2 from methane to increase the volumetric energy content in the gas. The removal of CO2 increases the methane heating value and Wobbe index[2] and gives a consistent gas quality like natural gas (Pramanik et al., 2019). This natural gas component in biogas increases its market value.

Therefore, constant monitoring of biogas helps to establish the methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S), and oxygen (O_2) in the raw and upgraded biogas; this is important for complying with the requirements of the gas quality (Aryal et al., 2021). According to Aryal et al., the process can further result in a product that is sufficiently pure to stand a chance as a commercial market offering. Therefore, the first investigation in this paper focuses *on establishing whether the biogas produced in Uganda is sufficiently pure to stand a chance as a commercial market offering.* To complete this investigation, we monitor biogas production at NaLIRRI and capture real-time continuous process data of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S), and oxygen (O_2) using Process Analytical Technology (PAT).

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[2] The quotient of the heating value and the square root of the relative density

Shaping sustainable biogas markets

Despite the high potentiality of biogas to cover the energy supply gap, its "pro-poor" public perception denies it recognition for business development. There is also a lack of quantitative and qualitative data from biogas to be considered by potential actors to make investment decisions. The limitedness of data could be explained by the reluctance of the state to invest in structures that cause potential actors to produce and supply quality biogas as a renewable energy source (Walekhwa et al., 2014). The transition literature denotes that the state is the lead actor in shaping renewable energy markets in the sustainable transition to clean energy (Alola et al., 2021); the state has a role to facilitate investments that shape sustainable markets through developing structures aimed at increasing production and generating the demand for energy that is cleaner than energy from conventional sources. Boon et al. (2020) add that valorising sustainable energy products require an effectuation process that involves several actors engaging in various activities and interactions aimed at changing the market structure and raising customer expectations. The actors are led by the state; the state can provide subsidies and favorable investment regimes. State support involves enabling discussions on strategies that help to raise public awareness, expectations, and resource mobilization (Frantzeskaki et al., 2017).

In shaping sustainable markets, the emphasis is on the role of transactions, customer segments, and end-user value propositions (Kamat et al., 2020). Ottosson et al. (2020) argue that shaping sustainable markets is driven by three key interrelated processes; enabling exchange practices, proving the system, and constructing the narrative. The success of this process is driven by activities involving both public and private actors at the intersection of product and financial markets. Enabling exchange practices includes demanding, supplying, negotiating, investing, and subsidization activities. Proving the system involves experimenting, validating, system building, providing equipment, producing, and using the gas. Constructing the narrative involves promotional activities, lobbying, envisioning, informing, and translating (Ottosson et al., 2020; Pansera & Sarkar, 2016). The activities in each process valorize sustainable products for market development and could help to mobilize monetary resources for building and operating socio-technical systems. Particularly, constructing the narrative creates the awareness needed to make biogas an acceptable, valuable, understandable, and plausible energy source in society. The value created from a combination of the above activities if applied to Uganda can lead to sustainable business development in the biogas social-technical system and reduce greenhouse gas emissions. However, transition scholars have argued that when shaping markets for sustainable products, analysing the production potentials and operations of existing firms is important to expose systems weaknesses and/or limitations, understand firm operations, and identify niche opportunities that are vital for product valorisation and market development (Frantzeskaki et al., 2017; Geels & Kemp, 2007; Köhler et al., 2019). In this context we ask, *would analyzing the current small-scale biogas producers help to establish systems weaknesses for valorization and opportunities for market development?* This understanding can be an important source of information for shaping the biogas market and informing investment decisions in Uganda

Market research

Market research is another way of valorising biogas products for customer value creation. It is the first step towards introducing an existing product or solution to new customer audiences who have not yet been reached or served. Actors can use market research as an innovative approach to aligning value-creating products to individual customer segments (Kamat et al., 2020). During market research, producers can understand the most promising customer target and the best product offering. Although Uganda has a large population with limited access to clean energy, it is difficult to assume that biogas would create value for everyone. Furthermore, through the processing of the digestate, several products like organic fertilizers, liquid soap, and others, can be valorised for market development. The market for these products needs to be established as their consumption would drive biogas production in Uganda. It is therefore important for producers to interact with prospective customers (Maurya, 2022) to understand their buying behaviour, customer habits and perceptions about energy from waste. Market research thus determines the extent of demand, the specific customer segment and the best product offering for the market. Besides establishing the needs of the market and the value the product will create for targeted customers, market research is important to establish dedicated product supply structures for the different customer segments (Mooi et al., 2018). Therefore, at this point, we ask, *what are the most promising customer targets for biogas products in Uganda?* The responses to this question create an important valorisation strategy for biogas in Uganda.

Certification and quality controls

Certification and control of biogas is an indirect valorization strategy that ensures that a high-value product is consumed by society. Certification has helped in growing the biogas market in countries like Germany and Sweden and has proven a valorization model for growth and increased demand for biogas (Lindfors et al., 2020). For example, laws guiding feed-in tariffs into the grid have guaranteed price that does not exploit the public while enabling predictable long-term investment and planning without placing the burden on the public. Quality standards on the other hand have been very important in creating consumer confidence by supplying high-quality biogas (Nordberg & Edström, 2003; Wellinger et al., 2013). Quality requirements may be specified concerning feedstock and substrate used to produce biogas and the final application of the gas or sustainability criteria. The quality of biogas in Uganda needs to comply with the sustainability criteria of reducing emissions but not exacerbating them like in the case of uncontrolled releases into the atmosphere. As small-scale plants are upgraded to a level of offering biogas on a commercial scale, certification and controls for biogas are important to regulate the system. This can work well where supplier companies are registered and branded, creating a highly valorized biogas product with a stable market. In this way, revenues will be sustainably realized from biogas, the clean energy supply increased, and greenhouse emissions reduced. Taken together, the findings obtained through an empirical analysis of the above biogas valorisation strategies could help to formulate a coherent business development case for sustainable biogas production that will serve to reduce greenhouse gas emissions. The next section explains the methodology used to empirically and comprehensively analyze how the above strategies can valorize biogas and make it a commercial market offering in Uganda.

4. Materials and methods

This study is empirical and action-research oriented. It uses mixed data sources and methods. These include case study analysis, in-depth interviews, informal consultations, observations, pilot production, and stakeholder analysis. In-depth interviews and the pilot production methods were used to study the case study pilot plant. Informal consultations and observations were used to study the case pilot plant and small-scale farmers producing biogas. The stakeholder analysis was applied to potential biogas and digestate customers and farmer segments. These different methods and data sources were used to check on each other to corroborate the findings obtained at the different stages of the investigation as explained below.

4.1. Case study Analysis

To identify a suitable case study for analysis of biogas production in Uganda, a field visit was conducted at two institutional plants. These two plants were National Livestock Resources Research Institute (NaLIRRI) zero waste plant and the National Water and Sewerage cooperation waste processing plant. The two plants were selected because they are the existing large and public-owned biogas plants open to in-depth research activities. The characteristics of the plant used to assess the suitability of the case study were the size of the plant, production capacity (volume of biogas produced per day) management of digestate (extent of value addition), biogas upgrading activities and methane production potential. From the two plants, NaLIRRI zero waste plant was a suitable case for this study because it had the considered characteristics. NaLIRRI is a sub-institute of the National Agricultural Research Organisation (NARO) focusing on livestock research in Uganda.

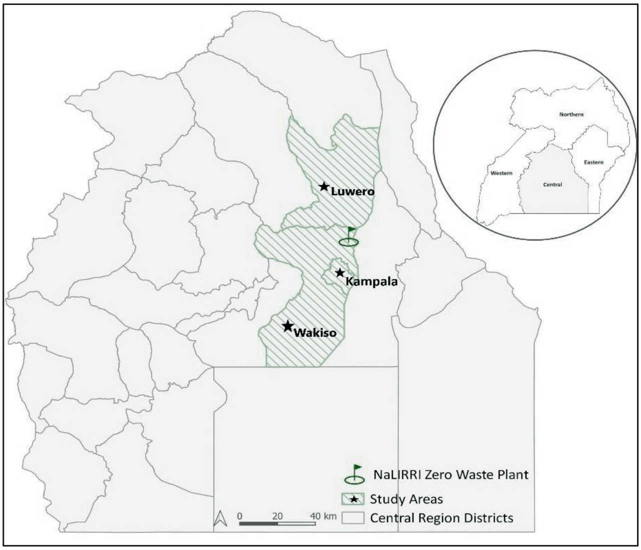

Figure 1: Case study area: NaLIRRI-Wakiso district, Uganda

The plant is in the central region of Wakiso district, approximately 36 kilometres north of the capital Kampala in Uganda. Figure 1 shows the location of the NaLIRRI zero waste plant. The plant was constructed in 2017 with funding from the Government of Uganda and is so far the largest public biogas production plant in the country. Biogas production is, however, not the main mandate of the institute but was adopted to utilize the large amount of animal dung produced by the livestock. The plant design is vertically annexed to a 300-capacity cattle shade but 132 were resident at the time of this study. The dung in the cattle shade is pushed down into a drainage using a scrapper and collected in a reception pit. Figure 2 shows the schematic layout of NaLIRRI zero waste plant.

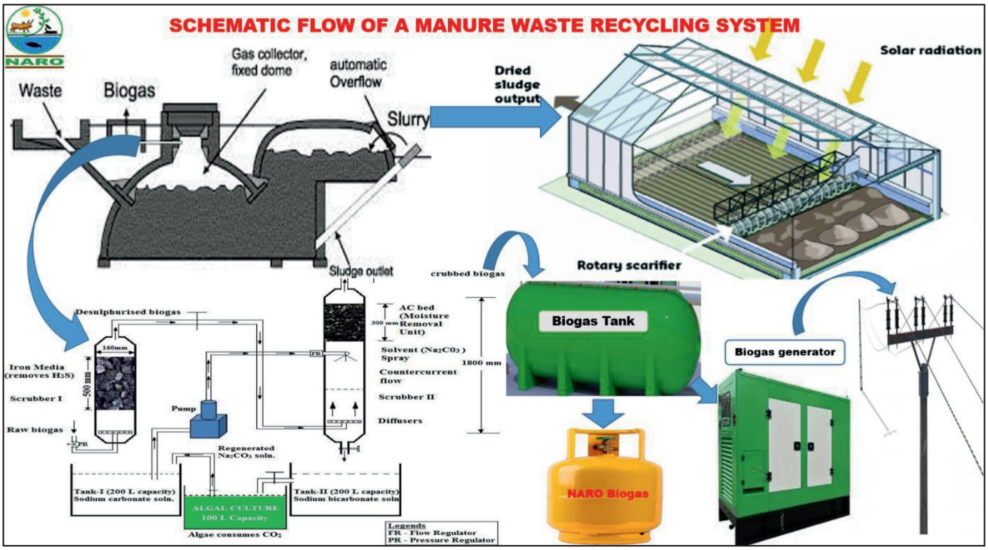

Figure 2: Schematic presentation of NaLIRRI zero waste plant; (obtained from NaLIRRI institute with consent to publish it)

The plant has two different but connected biodigesters of 58m^3 each, with a total capacity of 116m^3 equivalent to the energy production of 2552MJ and 9187kwh of electricity per day. The analysis at the facility was carried out as presented below.

4.1.1. semi-structured interviews

The observations made during the first visit to NaLIRRI guided a semi-structured interview that included a mix of questions related to the drivers for the valorisation of biogas for market development. The interviews were conducted face-to-face with the biogas program leader (in the office) and a biogas technician (moving around the site from the cattle shade through to the digestate collection point). During the discussions with the technician, the observation method was intensively used. The interviews were video recorded with consent from both parties and later transcribed by the researcher. The observed phenomena were recorded and incorporated into the transcription report. Because the methane quality that we aimed to investigate could not be observed through the interview process, we conducted a practical pilot production to observe the purity of methane at the plant.

4.1.2. Pilot production

In preparation for capturing the data on biogas purity, the researcher was physically and actively involved in the biogas plant operations for six months from March to July 2022 in the capacity of an intern. During this period, several issues regarding digester feeding mechanisms and operation, upgrading process, and management of the digestate were observed. The competencies and capabilities of the plant operators were also established in line with the effectiveness and efficiency of the biogas production and upgrading activities. In the pilot production, data readings of raw biogas (input) and upgraded methane (output) were recorded three times a day (morning, afternoon, and evening) for four weeks. Data readings of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S), and oxygen (O_2) in the raw and upgraded biogas were obtained and recorded in an excel template. Process analytical technology (dashboard biogas analyser) equipment was used to take the data readings.

Process analytical technology (PAT) is a system designed for analysing and controlling production through timely measurements of critical quality and performance parameters of raw and process intermediates (Aryal et al., 2021; Bakeev, 2010). The goal of using this technology is to monitor and control the process in real-time as early as possible in the production at strategically selected process locations with steps that ensure the quality of the final product. The PAT monitoring program is very vital in the early stages of production because it helps operators to understand the biological process of gas production which reduces reliance on the accumulated human experience (Wellinger et al., 2013). The rationale for using PAT is to increase and stabilize production yields by minimising all types of variations and keeping the process within optimal operation conditions at all times. This method also reduces the need (but never eliminates) for accurately determining analytical results from quality control laboratories (Bakeev, 2010). Furthermore, the process ensures continuous and controllable production of high-quality biogas, to meet a sustainable supply of energy in society as well as an optimized control of the fermentation process (Beil & Beyrich, 2013).

According to Khan et al. (2021) and Wellinger et al. (2013), the significance of monitoring the purity of biogas is to valorise its status for large-scale applications. The process also helps in the efficient supervision and control of fermentation processes including anaerobic digestion. This enhances plant performance for increased capacity and speed as well as increasing productivity without running any risk of process inability. Wilfert et al. (2004) found that measuring the exact gas purity gives valuable information about the process's stability and efficiency in terms of combustion characteristics of the gas like superior heating value[3], Inferior heating value[4], Wobbe index and relative density[5] (Wellinger et al., 2013). Furthermore, monitoring biogas production and composition facilitates continuous process improvement, production optimization, and achieving higher methane quality. This information is not only suitable for improving the system, but also for market development and policy decisions (Bakeev, 2010; Lindfors et al., 2019).

4.2. *Stakeholder assessment*

Apart from biogas, NaLIRRI is involved in the production of several products from the digestate. These products and biogas were grouped into product portfolios and corresponded with potential customer segments in a matrix form. The matrix was used to establish the most suitable customer segment for biogas and the other products from the digestate. Small-scale biogas producers (farmers) were also part of the assessed stakeholders.

4.2.1. Customer interest survey

A customer interest survey was conducted in March 2022. The survey aimed at establishing which product (among biogas and digestate products) has the most promising customer segments. The survey was administered to a total of 200 randomly selected respondents using online platforms (email, what's-up) and a face-to-face interaction method was used. Respondents were distributed across rural and urban households, including 48 Luwero (rural), 83 Kampala and 69 Wakiso districts (see Figure 1). The survey included an opportunity portfolio with different customer segments and the different products produced from waste in Uganda (e.g., bioelectricity/biogas, biofertilizer, mushroom growth media, animal pellets, liquid soap, and pesticides). Customers were free to choose more than one product. The respondents were asked to tick the product they thought is more important to serve their most pressing needs. That product

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[3] Higher/ upper heating value of gross energy or gross calorific value of the gas

[4] Net calorific value of lower heating value of the gas

[5] Quotient of the density of a distinctive gas and density of dry air at equal temperature and pressure

customers would be willing to buy if it was produced and commercialised on a large scale. A total of 196 customers responded to the survey.

4.2.2. Farmer interest assessment

For informal consultations and observations, we randomly visited ten (10) small-scale biogas farmers; three (3) in Kampala and seven (7) in Wakiso district in central Uganda (see Figure 1). The small-scale farmer category forms a large part of the supply side for biogas in Uganda. The group is also a starting point for business development activities since they already have established and operating biogas plants. Aside from validating the findings from NaLIRRI, small-scale biogas farmer assessments were important for establishing biogas availability, quality, and production volumes. This survey was also important to understand whether farmers are interested in doing biogas business and the efforts (if any) they have taken to achieve this goal. Another important aspect was to establish whether farmers had adequate knowledge of biogas and digestate valorisation. The survey was guided by eleven (11) key questions around which a discussion on biogas production and digestate management was built. The eleven questions and the farmers' responses are outlined in Table 1, Appendix II. Furthermore, we obtained secondary data on small-scale biogas production from SNV; The Netherlands development organization, promoting biogas production and utilisation in the East African region. These data were in the form of reports based on farmers' voices captured through interviews. We categorized the responses into three groups that represented farmers’ interests: “More attractive prices”, “Faster services” and “Better services”. We obtained and reported percentages for each response category using a pie chart, see figure 7.

5. Results

5.1. Qualitative results from case analysis

The interviews, observations, and pilot production conducted at NaLIRRI zero waste plant revealed several issues concerning biogas production, upgrading and management of the digestate.

Production stage

At the production stage, we observed that; 1) the dung from the 132 cattle heads was the only feedstock used to produce biogas. 2) The water used to clean the cattle shade is channelled through the manure drainage system and used for mixing the substrates in the reactor (no hydraulic-solid ratio measurement). 3) The water was often pumped out before agitation and disposed into external drainage to maintain the hydraulic-solid ratio required in the reactor. 4) The manure pit was open and doubled as the reactor. 5) The manure was agitated and pumped into two parallel digesters' once a week using a decanter centrifugal pump. 6) The dung in the manure pit was not continuously mixed, which caused a hard scum surface (see Appendix I). 7) The manure pit was designed in a square shape, and a circular-shaped agitator was dipped into the manure. 8) The agitator moves in a circular motion and does not mix the dung in all four corners of the pit; this causes dung sedimentation. 9) The sedimented manure affects the agitator movement causing it to break down. To ease movement, the agitator is manually rotated to create space for mixing (Refer to Appendix I). 10) The drainage channel and the manure pit were partly open which causes running water with external debris (sand, plastic bottles, and bags) to be eroded into the reactor (manure pit). This debris together with poor mixing causes further sedimentation, foaming, and a build-up of scum in the reactor. Finally, the biogas produced in the two digesters is directly channelled into the upgrading unit using 1-inch PVC pipes.

Upgrading stage

During upgrading, the gas goes through a frame arrester filled with an aqueous solution containing sodium hydroxide (NaOH) calcium oxide (CaO) and activated carbon. Activated carbon reduces H_2S and other impurities that might be in the raw biogas. Sodium hydroxide (NaOH) and calcium oxide (CaO) are for removing CO_2, although according to the pilot production analysis CO_2 removal did not work. From the frame arrester, the gas goes through a dehydration tower, a desulphurisation tower, a buffer tank, and a filter. The upgraded gas is pumped into a storage tank. Apart from the frame arrester, which was irregularly fed with the aqueous solution, the dehydration and desulphurisation towers were never checked or filled with any upgrading contents. The stored gas is converted into electricity using a generator and connected to the grid. However, the gas was observed to have water impurities at the filter stage and the gas composition results show the presence of H_2S and oxygen impurities at the output although in small amounts. Nevertheless, the interactions with the plant operators during the five months at this facility revealed a knowledge and competence gap in both the production and upgrading of biogas.

Digestate management stage

The digestate flows by gravity through closed retainer tanks and is stored in two parallel, open pits and treated by separation. A decanter centrifugal pump and screw press separator were used to separate the solid digestate from the liquid. The solid digestate is dried inside a solar drier (Refer to Figure 2) while the liquid is stored in two parallel open pits. The liquid digestate is used to make liquid soap, pesticides, and fertilizer while the solid digestate is applied on the institute farm as organic fertilizer to grow animal feeds. Other products produced from the solid digestate include pellets, mushroom growth media, and briquettes. Nevertheless, we observed that the digestate is left to stay longer in the open pits and becomes a breeding habitat for mosquitos.

5.2. Pilot production analysis

The input and output gas at the pilot plant was analysed daily for four weeks, with a sample size of three per day (taken in the morning, afternoon, and evening). X-bar/R control charts for input concentrations of methane (CH_4), carbon dioxide (CO_2), oxygen (O_2) and hydrogen sulphide (H_2S) are shown in Figure 3 and for output concentrations in Figure 4. Results indicate that the raw biogas (input) contains on average more CO_2 (44%) than methane (42%). Furthermore, the methane in the upgraded gas increased by 11%; this is an insignificant increase compared to the upper specification limit of 98%. There was also no significant reduction in the level of CO_2 after purification; the average was 41% compared to the 2% specification limit. This is an indication that the carbon dioxide removal process does not work.

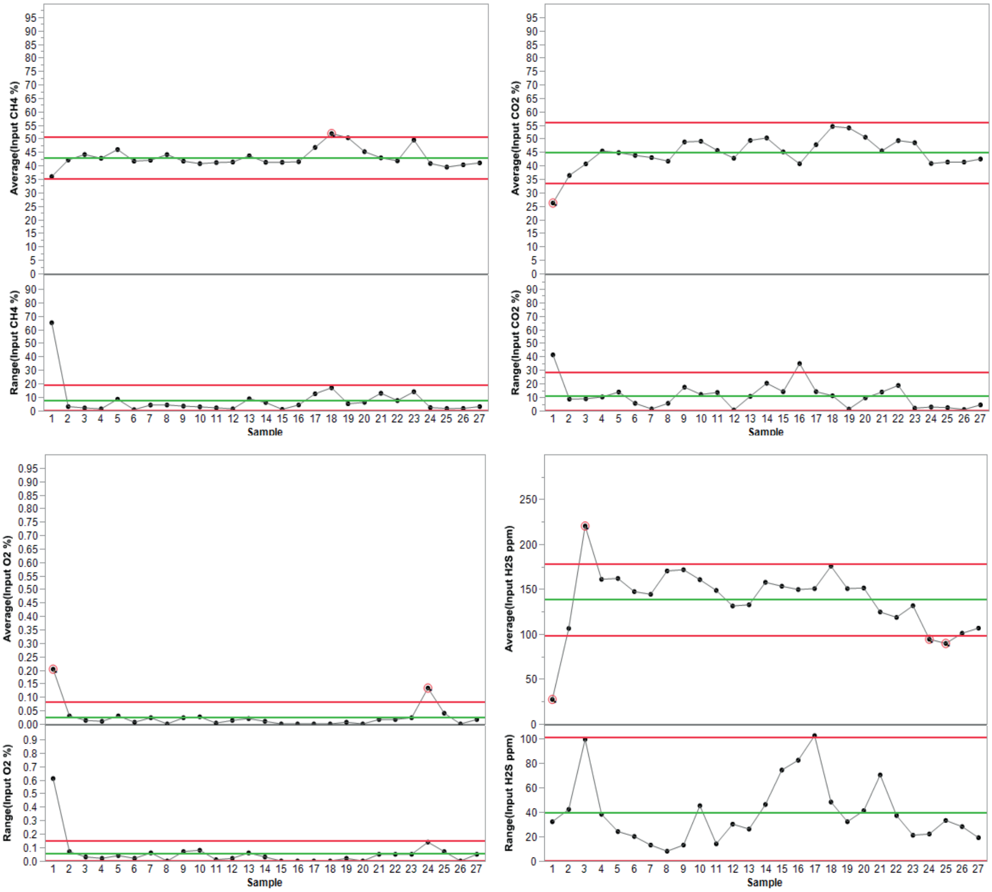

Figure 3. *X-bar/R control charts for input concentrations of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2) at the pilot plant (process means represented by green lines, upper and lower 3σ control limits represented by red lines, control limit violations indicated by circles around individual means)*

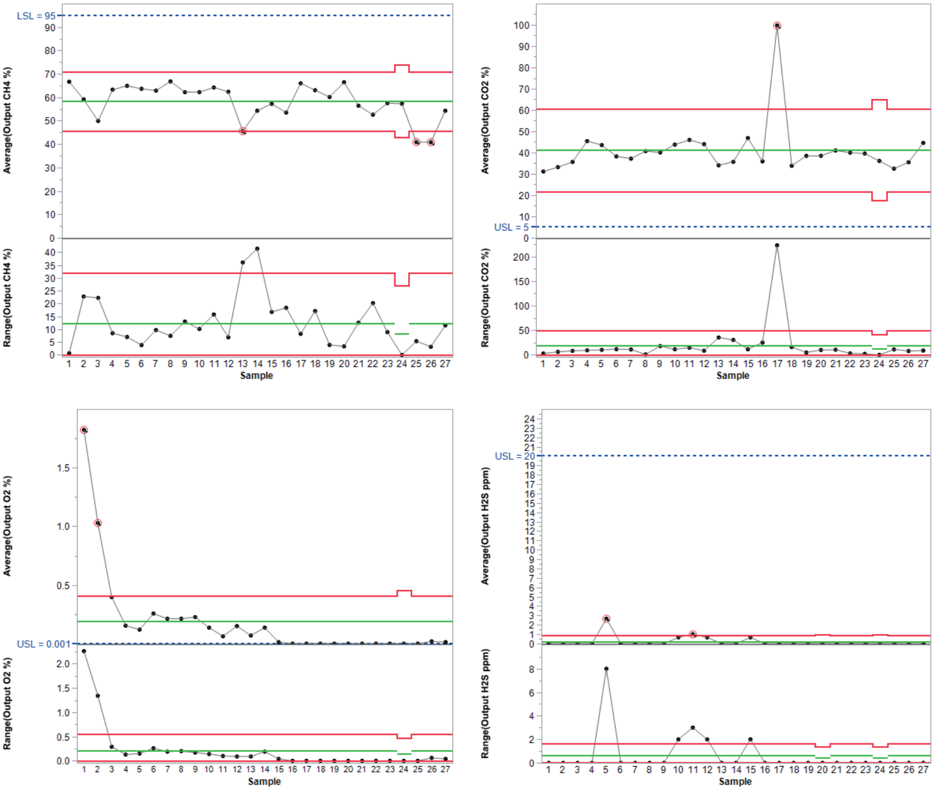

Figure 4. *X-bar/R control charts for output concentrations of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2) at the pilot plant (specification limits represented by blue lines, process means represented by green lines, upper and lower 3σ control limits represented by red lines, control limit violations indicated by circles around individual means)*

5.3 Stakeholder analysis

5.3.1. Customer interest analysis

The relative interest among different customer groups in the various biogas/digestate products was analysed based on the customer interest survey. In the first step, the indications of interest obtained from the customer groups were cross tabulated against the product categories that were included in the survey. In the second step, the resulting contingency table was subjected to correspondence analysis (CA). Together, the first three dimensions accounted for 80% of the total variation. Figure 5 shows biplots, in symmetric scaling, of customer segments (represented by blue dots) and product categories (represented by red dots; sizes proportional to frequency) on the first three dimensions.

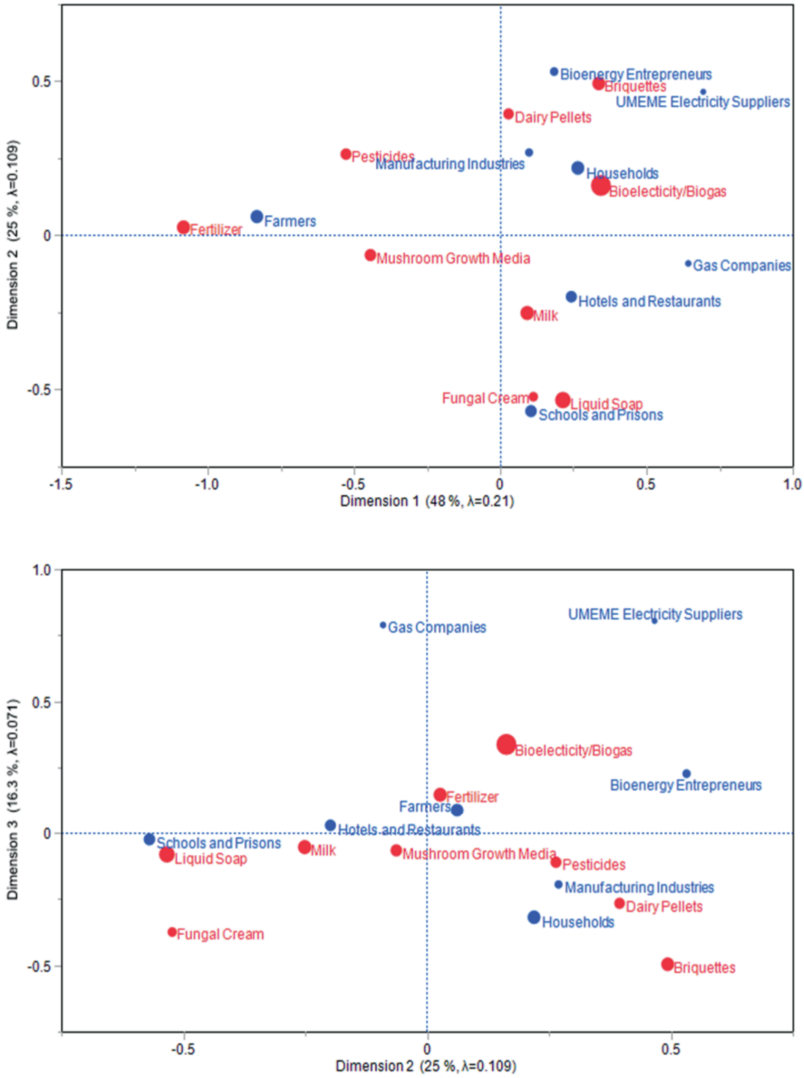

Figure 5. *Correspondence analysis biplots of customer interest in different biogas/digestate products (symmetric scaling; customer segments represented by blue dots; product categories represented by red dots; dot size proportional to frequency)*

In the third step, the coordinates of all customer segments and product categories on the first three CA dimensions were jointly hierarchically clustered, using Ward's method. The dendrogram is shown in Figure 6. The results show clear clustering of the product category, bioelectricity/biogas, with three customer segments: bioenergy entrepreneurs, gas companies and electricity suppliers. These can be regarded as the primary target and the most promising segments for bioelectricity/biogas products in Uganda, respectively.

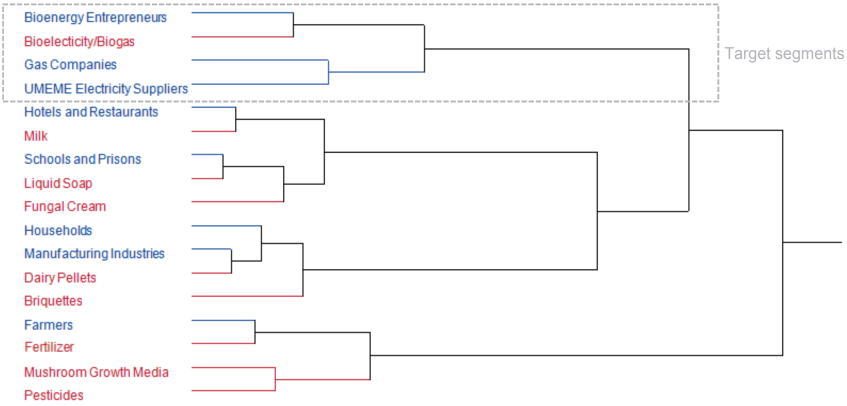

Figure 6. *Joint hierarchical clustering of customer segments and biogas/digestate products (Ward's method with correspondence analysis coordinates as inputs; customer segments in blue, product categories in red)*

5.3.2. Farmer interest analysis

Out of the ten (10) farmers, nine (9) were present at the time of our visit. The results in Table 1, in Appendix II, show that, out of the nine (9) plants, the smallest digester was 13m^3 while the largest was 65m^3. All the farmers used animal manure as feedstock for biogas production. The farmer with a 65m^3 digester produced biogas from cow dung, poultry droppings, and pig manure. Results further show that farmers do not know the volume of raw biogas they produce per day and all farmers used biogas for cooking. Two of the farmers used the gas for heating the chicken brooder while the seven farmers used the gas only for cooking. Four (4) of the nine farmers reported that they manage the excess gas by releasing it out into the atmosphere. One of the farmers who stays at a different location from the farm reported that the gas is pumped into a car tire tube and carried home for cooking although it was still a lot. Farmers who reported producing more gas than they need/ use also reported that they wish to sell the gas, but they have no way of doing so.

All farmers reported that they use the digestate in the garden as fertilizer. Three (3) farmers indicated that they also sell the digestate as fertilizer to other farmers without biodigesters. For detailed results of the farmer survey, refer to Table 1, Appendix II.

The results analysed from SNV-The Netherlands Development Agency report are presented in Figure 7. From the Figure, 74% of the farmers need faster response services, 22% need better services and 7% of the farmers need attractive prices. This means that 74% of the farmers indicate that technicians are very scarce and hard to get. There is thus competition for the available technicians and once there is a problem with the digesters, it takes a long time to be fixed. In Figure 7, 22% of the farmers reported limited knowledge of the available technicians. Technicians could not solve all the challenges farmers face with the digesters and thus provide poor services. In the Figure, 7% of the farmers reported that the initial cost of acquiring the digester and the cost of repair is high and therefore not attractive to other farmers who would wish to install biogas systems.

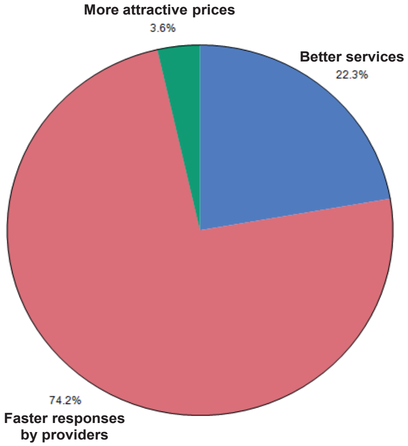

Figure 7. *Results of farmer interest analysis*

6. Discussion

A general analysis of data from different sources reveals that the biogas industry is a business that provides one service and two products. The service is waste management which happens when waste is processed, and the product is biogas and digestate. Valorization of these products increases their market chances while reducing the greenhouse gas emissions that come with their mismanagement and misuse. The results from the pilot plant reveal that although the plant produces a lot of dung to sufficiently produce high volumes of biogas, processing of the dung is poorly managed. From the results, there is poor mixing of the slurry and hydraulic-solid ratio measurement; running rainwater erodes unwanted material into the manure which causes sedimentation and dilutes slurry mixtures. According to Schnürer and Jarvis (2018) and Wellinger et al. (2013), poor substrate mixing reduces biogas yields and affects methane quality. The erosion of external material by running water into the reactor reduces the active volume of the digester and increases the hydraulic content of the slurry which inhibits fermentation, methane yield and quality of the raw biogas. From the results, the open manure and digestate pits and the drawing of the unprocessed wastewater from the manure pit into external drainage could reduce the volume of methane in the raw biogas and cause methane slips leading to emissions (Wellinger et al., 2013). These results indicate major biogas production deficiencies at the pilot plant. Improving such biogas production deficiencies valorises biogas (improves production volumes, and methane quality and attracts demand into new uses) (Llamas et al., 2020); this could develop the product to increase its market chances while reducing greenhouse emissions in Uganda.

Additionally, the limited knowledge of biogas production processes observed at the facility could affect the performance of the plant. Important to note, NaLIRRI is a public research institute that transfers knowledge of their works to other researchers. The expectation is that proper knowledge evaluation on substrate mixing, and other biogas production processes are important to translate to interested researchers, private investors, and entrepreneurs for replication. Translating the right knowledge creates learning which valorises the entire biogas industry to develop the biogas product, can scale the sector and lead to market development while reducing global warming from greenhouse emissions (Ottosson et al., 2020)

Results on whether the biogas produced in Uganda has the desired quality of 98% methane to stand a chance as a commercial market offering show high variance over the pilot period in terms of all measured quality indicators; control range violations were observed on all quality indicators. Figure 4 shows that the pilot production process never even got close to the lower specification level of 95% for upgraded CH_4 and the upper specification level of 5% for CO_2 in the output gas. These results reveal that the biogas produced at NaLIRRI does not reach the standard quality of 98% methane to stand a chance as a commercial market offering. This implies that to result in a commercial market offering, the valorisation of biogas through continuous monitoring trials of upgrading solutions is important to reach the required purity of the gas. Through continuous monitoring, the plant performance can be improved until the right methane quality is achieved. Once the right quality is achieved, and a high-quality product is availed, the demand can be generated through market development. Thus, the valorisation of biogas through monitoring its purity can lead to market development and help to reduce greenhouse emissions in Uganda. From the findings, a focus on improving CO_2 scrubbing can be strongly recommended. Furthermore, the average methane value of 44% in raw biogas indicates higher production potential compared to 32% per cubic meter estimated in cattle manure by Rutz and Janssen (2013). Schnürer and Jarvis (2018) and Rutz and Janssen (2013) found that animal manure has a lower methane content compared to other feedstocks because anaerobic digestion is its second phase of digestion and has less volatile fatty solids (VFS) and low total solids.

However, although the average methane number obtained from the cattle manure at NaLIRRI is higher than the estimations by Rutz and Janssen (2013), the range for both methane and carbon dioxide in the raw biogas shows high fluctuations. Such fluctuations could be explained as resulting from instabilities and perturbations in the fermentation process (Khan et al., 2021; Schnürer & Jarvis, 2018; Wellinger et al., 2013). Similarly, Khan et al. (2021) argue that low methane yield and high carbon dioxide recorded in the raw biogas are indicators that fermentation was disturbed and thus not completed. More CO_2 than CH_4 is expected in the gas at the beginning of the fermentation process or when fermentation has been disturbed (Pramanik et al., 2019). Methane and CO_2 rates are usually stable during the process, but when fermentation is disturbed, their rates will fluctuate. These fluctuations in the ratios might also depend on other factors such as substrate quality and composition, process temperature and pH (Wellinger et al., 2013). The implication of this argument to our findings is that the substrate management and mixing observed at NaLIRRI are likely to be affecting the fermentation process and the methane quality of biogas. Therefore, valorising these areas of production will be equally important for a better biogas product.

From the results of the pilot production, in the output gas, we can conclude that the purification (NaOH) solution might be saturated with $CO_{2,}$ or the contact time and area of the raw biogas and the upgrading solution is not long or big enough for sufficient absorption and indication that the upgrading technology at the plant could be inadequate. Furthermore, a methane number of 58% obtained after purification could indicate that the biomethane gas is wet; the water-cleaning process could also be inadequate. Wet biomethane requires additional treatment before the gas is used to avoid a reaction with the H_2S impurities observed in Figure 4. According to Koenig and Dehn (2016) and Aryal et al. (2021) a reaction of wet biomethane and H_2S results in sulphuric acid (H_2SO_4) which corrodes metallic components and acidifies equipment and engine oils. Nevertheless, the process is, efficient for cleaning H_2S and the O_2 levels are below 5% which is too lean and non-explosive (Aryal et al., 2021). The significance of the above results is that monitoring biogas purity is an important strategy for valorizing biogas. The process helps to increase methane which is the gas of interest for monetary exchange in the biogas value chain (Beil & Beyrich, 2013). Such findings would not be possible without actual monitoring of the biogas quality. Therefore, the process should be considered by biogas producers as it will enable biogas to result in a product that is sufficiently pure to stand a chance as a commercial market offering and reduce emissions in Uganda.

While exploring shaping sustainable markets as a valorisation strategy, we analyzed biogas production from the small-scale biogas producer perspective. The purpose was to establish systems limitations for valorization and opportunities for business development. Results from the farmer interest survey reveal some systems weaknesses such as, small-scale biogas producers do not know the exact amount of gas they produce, and the farmers release biogas into the atmosphere, which indicates that they produce excess capacity than what they need to use. This finding relates to the works of Bluemling et al. (2013). The act of releasing the gas confirms the “environmental nuisance” happening in Uganda. The survey also shows that farmers desire to sell the excess biogas but are limited by upgrading and packaging technology to do business. The implications for these findings are that the weaknesses reveal the need for the valorisation of biogas while the desire to sell biogas reveals the importance of shaping sustainable biogas markets. The significance of the results is that biogas production from small-scale producers can attract business development although this could be on a small scale, given the size of the farmers' digesters (mainly $13m^3$). Lacking upgrading and packaging technology on the other signifies that there is a technological gap required to link the biogas product to the external market (from the producer to the customer). Future research needs to explore innovative options for filling this gap. Therefore, to fulfil the farmers' desires while valorising biogas, there is a need for state actors to engage in technological innovation, such as the one recommended by Namugenyi et al. (2022). Technological innovation transforms biogas systems through value addition (Nevzorova & Karakaya, 2020). This transformation can thus valorise biogas to stand a chance as a commercial market offering while reducing greenhouse emissions in Uganda.

Furthermore, the voices of farmers reported in Figure 7 revealed that 74% of farmers could not easily access technicians on time (faster response from providers) which required long waiting times to fix technical digester problems. On the other hand, 22% of farmers needed regular visits for quality checks and to improve their biogas plants to productive levels (better services); Such a response resonates with the findings from the case analysis and implies that there is a technical skills gap in Uganda's biogas industry. This is a major limitation in rapidly valorizing and scaling up biogas projects. However, Nevzorova and Karakaya (2020) and Rupf et al. (2016) found that although training technicians requires significant resources, for biogas projects to grow quickly, skilled installers, producers and technicians are required. Skills development contributes to the valorization of biogas and can increase private investment in the sector. This finding is thus critical to the government of Uganda and development agencies to consider putting in place systems that support the development of human resources, such as targeted courses on biogas solutions at technical institutes.

To explore the market research valorisation strategy, we investigate the most promising customer segments for biogas products in Uganda. The results in Figure 6 shows clear clustering of the product category, bioelectricity/biogas, with three promising customer segments: bioenergy entrepreneurs, gas companies and electricity suppliers. This means that the most promising customer segments for biogas are the bioenergy entrepreneurs, gas companies and the incumbent hydroelectricity suppliers (UMEME contractors). This finding is significant for producers as it helps to understand the exact customer target for biogas in Uganda. Following the arguments of Blank (2020), there is no value in producing a product that does not appeal to the market. The findings from our results thus, encourage the valorization of biogas for market development since the best customer target is known. The findings also show the importance of market research as a driver for the valorisation of biogas for increasing its market chances. The availability of a ready market can further lead to sustainable and productive use of biogas which could reduce emissions in Uganda.

6.1. Digestate management

Digestate is the other product from waste that is generated as a residue from biogas production. Besides organic fertilizers, which is the most sustainable way of using the digestate, NaLIRRI recycles several innovative products although being a government institute it has no mandate to do business and thus cannot produce and sell the products at a commercial scale. These products are thus produced on a small scale and used internally at the farm. The innovation of multiple products from the digestate implies that biogas production is a rich industry that can integrate different sectors and stakeholders along the value chain. Furthermore, the customer survey revealed that some customer segments are willing to buy products made from digestate. This implies that these products should be made available, and a narrative constructed around them to create an organic market base. The availability of a customer base for such organic products also signifies that the biogas industry necessitates the involvement of other actors from several sectors like entrepreneurs, economics, political economy, and researchers to focus on its growth and development (Lindfors et al., 2020). The activities of the different stakeholders require continued implementation through support systems to create a transition towards sustainable production and growth of the biogas industry in Uganda. This support should be simultaneously integrated into policy frameworks and directed towards exploring innovative products from the digestate and shaping sustainable markets for biogas.

6.2. Limitations and reflections

Throughout the investigations, several limitations were encountered. First, there were no previous data readings recorded on the purity of biogas at the pilot plant to compare with the one this study collected. This made the data readings in this study the first of its kind at the facility which seems abnormal. Secondly, despite having all the basic technology in place, the facility lacked a well-coordinated and knowledgeable biogas production team to take care of the raw biogas production and upgrading processes. This limited our understanding of the background of the system's deficiencies observed and reported in this study. Thirdly, biogas production systems in Uganda are underdeveloped with small-scale plants scattered across the country in farming communities and households. Valorisation of biogas from such small-scale plants might require innovation of new technology; for example, upgrading technology that is compatible with the micro-size biodigesters like the ones owned by the small-scale farmers in Uganda. Such technology might however be expensive to acquire by farmers and would-be entrepreneurs. Fourth, many non-biogas-producing customers (especially households) had no idea about biogas energy and its working principle. This required the researcher to explain a lot to make them understand the purpose of the customer survey. Future research should focus on addressing these limitations. Particularly, studying the innovation and development of upgrading technology prototypes that are compatible with micro digesters and affordable to farmers and entrepreneurs. Such technology will valorise biogas into a commercial market offering and link producers with the market. This will further help to reduce greenhouse gas emissions in Uganda.

7. Conclusions and recommendations

This study aimed to explore the valorisation of biogas to stand a chance as a commercial market offering and reduce greenhouse gas emissions in Uganda. During the investigations, we used mixed data sources and methods. Using different methods and data sources, the study explores and empirically investigates different strategies for valorising biogas into a commercial market offering in Uganda. The results reveal that the biogas produced in Uganda does not have the desired quality of 98% methane to stand a chance as a commercial market offering; the pilot production process never got close to even the lower specification level of 95% for upgraded methane (CH_4) and the upper specification level of 5% for carbon dioxide (CO_2) in the upgraded gas. The study also found that small-scale biogas producers have excess gas which they release into the atmosphere; with a high desire to sell it, but with no idea of how to valorize the gas to reach the market. Furthermore, clear clustering of the product category, bioelectricity/biogas, revealed three promising customer segments: bioenergy entrepreneurs, gas companies and electricity suppliers.

The results signify that to become a commercial market offering, the purity of biogas needs to be improved using valorisation technologies (new upgrading units tailored to micro-level digesters) and strategies like monitoring gas quality, shaping the market, market research and certification and controls. Continuous monitoring of biogas composition helps to establish the purity of the gas; shaping sustainable biogas markets (constructing the narrative, proving the system, and enabling exchange practices) can help in the commercialisation and diffusion of biogas, market research helps to establish the right product for the right market; certification and quality controls help with regulating the sector. Taken together, these elements can valorize biogas, to stand a chance as a commercial market offering which will reduce its wastage through uncontrolled releases into the atmosphere. From the findings, we can also conclude that there is a high but unexploited potential in Uganda's biogas industry; the industry is still a niche market that requires technological innovation tailored to micro-level digesters. Technological innovations tailored to micro-level digesters will help to convert excess gas from farmers to biomethane and increase the methane value to 98% (because methane is the gas of interest for monetary exchange). Valorization of biogas will also allow for its integration into future sustainable energy supply, and increased access to clean energy in Uganda.

Uganda's bioenergy policy needs to consider the valorization of biogas to increase its market chances. The policy could consider subsidization of biogas valorisation technologies for affordability by farmers. For positive outcomes, policymakers need to first understand why the biogas infrastructure is not developed despite being funded. A keen understanding of the biogas valorization strategies discussed in this paper can be an important policy guide; the findings will be significant for making investment decisions into new technologies tailored to micro-level productions. National policies should also support technical capacity building and training to meet the skills demand for a growing biogas market. Finally, as part of the valorization process, policy instruments in Uganda should work to ensure that for environmental reasons, all waste and residues are converted into biogas and biofertilizer with full utilization of the biogas produced.

Acknowledgements

We thank the management and staff of NaLIRRI for allowing us to use the facility and for providing all the relevant information and materials we needed to complete this study.

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Appendix I

Manual operation of the agitator dipped into sedimented manure

Appendix II

Table 1: Farmer survey responses

		Farmer responses								
No	**Question**	**Farmer 1**	**Farmer 2**	**Farmer 3**	**Farmer 4**	**Farmer 5**	**Farmer 6**	**Farmer 7**	**Farmer 8**	**Farmer 9**
1	**What is the source of your biogas?**	Poultry droppings (12,000 birds)	Cow dung (8cows)	Cow dung (4 cows)	Pig manure (500 pigs) and chicken droppings (2000 chickens)	Pig manure (180 pigs)	Cow dung (15 cows)	Pig manure (350 pigs) and chicken droppings (10,000 chickens)	cow dung (3 cows	Cow dung (10 cows) poultry droppings (15,000 chickens) Pig manure (150 pigs)
2	**Do you know the capacity of your digester?**	50m3	13m3	13m3	60m3	13m3	26m3	50m3	13m3	65m3
3	**Do you know how much biogas you produce per day?**	No	No	Not sure	No	Not sure	Not sure	No	No	No
4	**Do you think you produce more gas than what you need/use?**	Yes	Yes	Not sure	Yes	Not sure	Not sure	I produce a lot	No	yes
5	**If yes, how do you manage the excess gas you produce?**	I pump it into car tyre tubes and take it home for cooking. I release most of it out	I release it out		I release it out			I use it for heating the brooder and cooking		I release it out
6	**Do you know the effect of the gas you release on the environment?**	Yes, I do	Yes, I do		No			I do not release my gas		Yes
7	**For what purpose do you use the gas you produce?**	Heating poultry brooder and cooking	Only cooking	Cooking	Only cooking	Cooking	Cooking	Heating and cooking	Cooking	only cooking

8	**Are there other ways you would wish to use the gas you produce other than the purpose you use it for now?**	yes, I wish I could sell my gas because it’s a lot	I would like to sell it if I have a way		I need a generator to convert the gas into electricity	No	I don’t think I produce a lot	I want to sell my gas	I have no idea	I need to sell the gas
9	**What attracted you to have/use biogas?**	Had a lot of chicken droppings, and I was advised to make biogas	Through training in farming	From a friend	From my neighbour	Agricultural training	Training	Agricultural show	Attended a training	From agricultural training
10	**Apart from manure, do you use any other feedstock to produce biogas?**	No	No	No	No	No	No	No	No	No
11	**How do you manage the digestate from your biogas production?**	I put it in the garden	I put it in my banana plantation	I sell some and use the rest in my garden	I use it in my garden	I sell some and use the rest in my garden	I put it in the garden	I put it in the garden	I use it in my garden	I sell and use some

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Thesis. 2023: 15
ISSN: 1894-6402
ISBN: 978-82-575-2044-1

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Paper 1 investigates whether biomass innovations improve households' subjective well-being by comparing traditional with improved cookstoves. Using survey data, results found improved cooking technologies to break households' intangible cooking-cultural ties, which lowers their subjective well-being.

Paper 2 examines the energy efficiency associated with improved cookstoves under traditional cooking routines. Results reveal that Uganda's traditional cooking routines devour the efficiency associated with improved cookstoves if used under similar routines.

Paper 3 assesses the entrepreneurial potential and feasibility of developing a mobile system for purifying and bottling biogas in portable cylinders for wider society consumption and benefit. Using a Transitional Model Canvas and a Feasibility study, results show that biogas has entrepreneurial potential and can improve energy supply and access in developing countries.

Paper 4 explores the strategies for valorising biogas to increase its commercial marketability and reduce its contribution to environmental damage. Results from pilot production and survey data reveal an existing potential for the biogas business but its quality is lacking and associated with methene emission to the environment.

The thesis recommends the need for policies (like technological innovation and subsidization) focusing on market development for biogas to drive the clean energy transition.

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ISBN: 978-82-575-2044-1
ISSN: 1894-6402

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