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

Irene Namugenyi [a,b,*], Lars Coenen [c,d], Joachim Scholderer [a,e]

[a] Norwegian University of Life Sciences, School of Economics and Business, Chr. Magnus Falsens Vei 18, NO-1433, Ås, Norway
[b] Makerere University, Makerere University Business School, Plot 21 A, Port Bell Rd, Kampala, Uganda
[c] Mohn Centre for Innovation and Regional Development, Western Norway University of Applied Sciences, NO-5020, Bergen, Norway
[d] TIK Centre for Technology, Innovation and Culture, University of Oslo, NO-0317, Oslo, Norway
[e] University of Zurich, Department of Informatics, Binzmühlestrasse 14, CH-8050, Zurich, Switzerland

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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 bio-products (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

* Corresponding author. Norwegian University of Life Sciences, School of Economics and Business, Chr. Magnus Falsens Vei 18, NO-1433, Ås, Norway.
E-mail address: irene.namugenyi@nmbu.no (I. Namugenyi).

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

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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

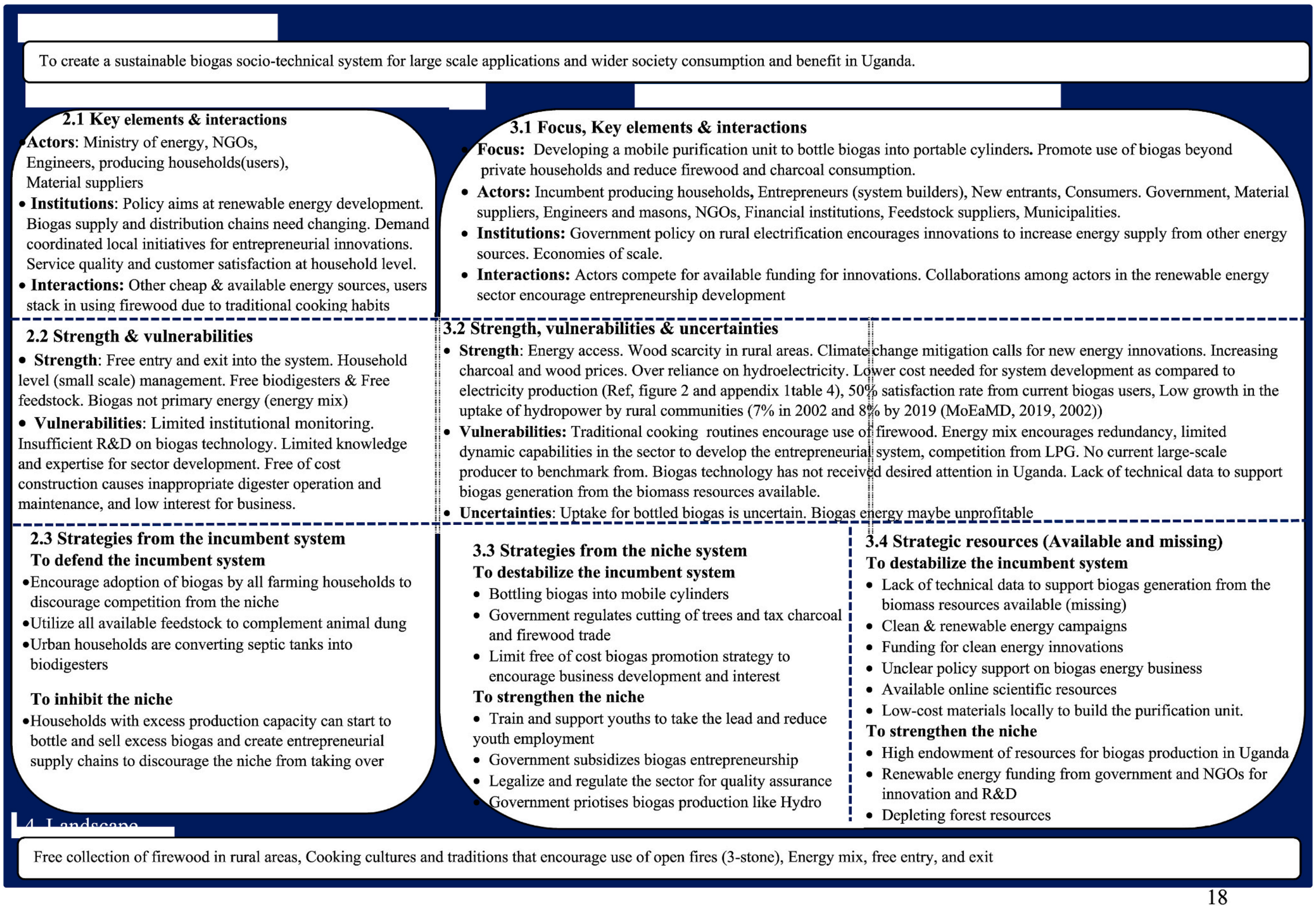

Fig. 1. Transitional model canvas for biogas technology in Uganda.

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

[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

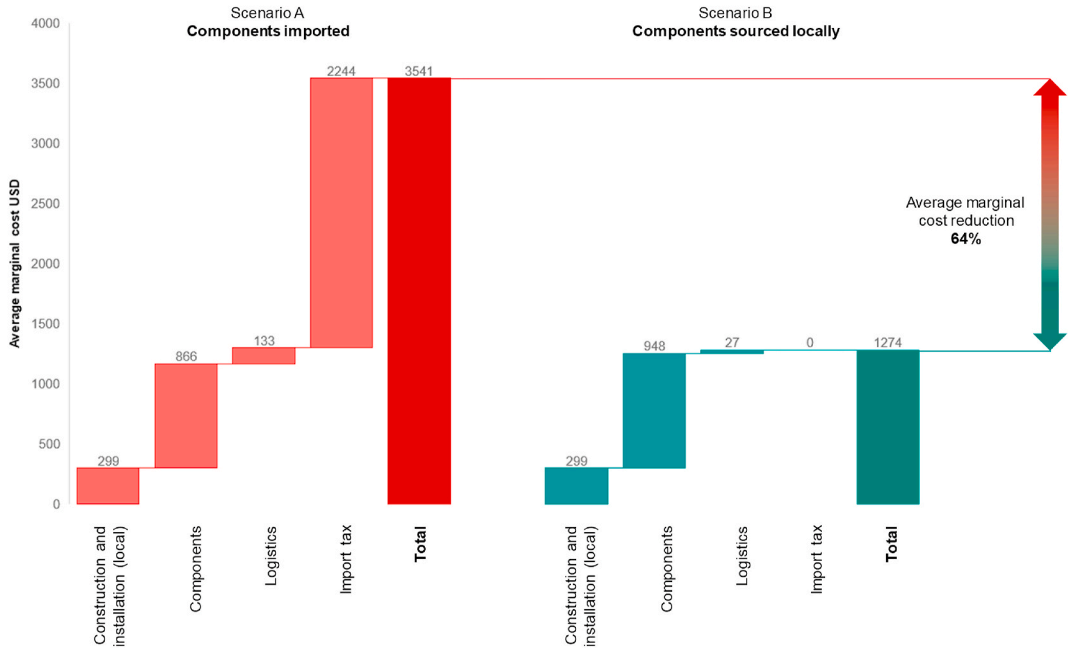

Fig. 2. Comparison of the average marginal costs (USD) between scenarios with the import of components versus local sourcing of components.

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.

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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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