MECS Modern Energy Cooking Services

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Portable Biogas: Assessing the socio-economic viability of packaging and distributing ready to use biogas

CREATIVenergie, ECHO East Africa Impact Centre & Unconventional Solutions

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Loughborough University

ESMAP Energy Sector Management Assistance Program

Portable Biogas:

Assessing the socio-economic viability of packaging and distributing ready to use biogas

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Executive Summary

Biogas digesters produce a clean and modern alternative cooking fuel. However, despite its benefits, biogas use in Sub-Saharan Africa remains low, with charcoal and wood fuel accounting for the majority of energy for both rural and urban domestic cooking. Numerous barriers hinder the scaling of biogas technology including: the capital cost to construct biogas digesters; the need for a supply of organic matter to input into it e.g. cow dung or food waste; and socio-cultural acceptability of the technology. Consequently, biogas digesters are both unaffordable and unfeasible for many households. Maintaining functionality of biogas digesters has also proved challenging, with some digesters falling into disrepair.

This project explored models of packaging and distributing surplus biogas, to assess the socio-economic viability of both facilitating an affordable, reliable and sustainable supply of household cooking fuel in rural and peri-urban areas and creating a scalable and sustainable income for households and communities with digesters. We present the results of a technology trial of some low-cost filling and distribution technologies alongside a socio-economic feasibility assessment of different distribution models. We assessed the viability and limitations of the distribution and trading models, and how such approaches could make biogas fuel more accessible, affordable and desirable, hence off-setting charcoal and wood stoves. Our study was focused in the Arusha region of northern Tanzania.

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1 Introduction

1.1 The Challenge

3 billion people cook with polluting fuel/stove combinations[1]. 4 million people p.a. die prematurely from illnesses attributed to household air pollution resulting from cooking on solid fuel[2]. Access to clean cooking facilities is only 2% in Tanzania[3], compared to 17% in sub-Saharan Africa as a whole[4]. Biogas is a clean, low-carbon alternative to traditional cooking fuels, usually supplied domestically through installing individual digesters. Yet barriers to access and widespread adoption remain: low/irregular incomes prevent people purchasing digesters (upfront capital costs are relatively high despite subsidy and limited access to credit[5]; insufficient quantities of proximate water and waste organic matter make constructing a digester unviable[6]; digesters fall into disrepair if not fed and maintained long-term (lack of committed/skilled labour)[7]. CREATIVenergie and ECHO's experience of monitoring Tanzanian household digesters suggests that biogas generated is underutilised for cooking and digester storage capacity is limited. Excess gas is currently released to the atmosphere via a natural pressure release existing on most digesters meaning that potentially useable fuel is wasted. Methane has much higher radiative efficiency than CO_2, and over a 100-year time horizon is considered to have 28-36 times greater impact than CO_2[8]. Hence, from a climate change perspective, the quantity of escaping gas needs to be minimised.

Existing biogas programs tend to only promote the installation of individual household digesters in Sub-Saharan Africa. Africa based biogas programs are overseen by the Africa Biogas Partnership Programme (ABPP), with national programs operational in Ethiopia, Kenya, Uganda and Burkina Faso. The Tanzania Domestic Biogas Program, a public private partnership with ABPP, was hosted by the Centre for Agriculture Mechanization and Rural Technology (CAMARTEC), from 2009-17[9]. ABPP aims to provide access to biogas in partnership with NGOs, local enterprises and governments and has to date primarily focused on the installation of individual household digesters. The consequence of this is that biogas programs do not automatically contribute towards the Sustainable Development Goals' aims of "leaving no one behind", because people need to have access to cattle (for dung) or other sufficiently large quantities of waste organic matter as a feedstock to operate

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[1] United Nations (2018)

[2] World Health Organisation (2016)

[3] ESMAP (2018)

[4] International Energy Agency, 2018, https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking

[5] Barriers and Opportunities of Biogas Dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India and Nepal, 2015, Rupf el al. Also see Barriers to Biogas Dissemination in India, A review, 2018, Mittal et al.

[6] Ibid

[7] Ibid

[8] https://pubs.rsc.org/en/content/articlelanding/2018/em/c8em00414e#!divAbstract

[9] https://www.africabiogas.org/countries/tanzania/

a biodigester and have sufficient financial resources to cover the up-front investment costs. Furthermore, the ABPP does not have a specific strategy on inclusiveness beyond encouraging subsidisation and creating access to credit[10].

1.2 The Opportunity

In response to the above challenges we identified an opportunity to explore alternative approaches to increasing the accessibility and affordability of biogas fuel without mass installation and ongoing maintenance of ever-increasing numbers of individual household digesters. Specifically, we envisaged peer-to-peer distribution and pay-as-you-go (PAYG) purchasing of ready-to-use biogas fuel alongside exploration of more efficient ways to cook with this supply of clean fuel. Creating a system for sharing biogas fuel aligns with DfID's priority of helping the poorest and most vulnerable by enabling households who cannot own biogas production assets to still have greater access to this clean and affordable fuel supply. We anticipated that this approach would provide value for money: distribution and trading of surplus biogas fuel reduces the amount of capital investment required per capita to access this clean cooking fuel and gives a greater return on investment (ROI) for the existing production assets. Additionally, we see potential in peer-to-peer distribution of biogas fuel facilitating prosperity through the creation of new income-streams and employment/entrepreneurial opportunities.

1.3 Aims of the Project

This project aimed to explore the viability of increasing access to an affordable and sustainable modern cooking fuel through the collection and distribution of surplus biogas from domestic and commercial digesters. Specifically, we set out to:

i. assess the technical feasibility of collecting surplus biogas before it is released to the atmosphere and package this for distribution;
ii. explore the socio-economic feasibility of different models for the distribution of packaged biogas, in order to facilitate pay-as-you-go purchase of biogas fuel.

1.4 Objectives of the Project

In order to achieve these aims we used a combined social science and technical prototyping methodology in order to explore the feasibility of our proposed approach. Our objectives were:

i. Develop and trial a low-cost filling device that channels biogas into bags when a biogas digester reaches its maximum gas capacity, whilst also

[10] Africa Biogas Partnership Programme (ABPP), Phase 2, Effect Evaluation, Final Report, May 2019, Fair & Sustainable Consulting

ensuring that the supply of gas to the household owning the digester is not interrupted and only surplus biogas is collected for distribution.

ii. Carry out a health and safety assessment of the processes of filling, storing and transporting biogas bags.
iii. Assess the viability of a household using a biogas filling device in practice.
iv. Conduct initial field trials of different biogas distribution models (peer-to-peer, milk round) and assess the socio-economic viability of the different models based on stakeholder feedback.
v. Examine whether there are cost and time savings in cooking with biogas 'rice' cookers compared with biogas stoves (gas ring burners) in household settings (rather than a lab), comparing how long/how many meals a family would be able to cook on these two appliances using packaged biogas.
vi. Explore user acceptability of biogas in bags to cook on gas hobs and with 'rice' cookers and compare the two options.
vii. Trial a low-cost biogas compression system and assess its technical viability in an African context.
viii. Assess the potential value of using smart technology in facilitating the trading and distribution of surplus biogas e.g. an SMS gateway and a GPS biogas bag tracking system.

2 Methodology

This project adopted a mixed method approach to data collection and analysis. Essentially there was a technical (quantitative) element and a socio-technical (qualitative) element. The two approaches were used in combination to collect a rich data set on the technical and socio-economic feasibility of portable biogas. Technical implementation, findings and limitations are discussed in Section 3 below, whilst qualitative insights and limitations are given in Section 4 below.

2.1 Technical Prototyping

We aimed to test the viability of containerising biogas from existing digestors in Northern Tanzania. Previous collaborations between CREATIVenergie and ECHO East Africa Impact Centre, indicated that biogas generation by household digesters exceeds consumption, and consequently gas is being released back into the atmosphere. In order to capture surplus biogas, making it portable, we had to determine what sort of container to use. After extensive consultation with our project partners in Tanzania, it was agreed that the initial line of enquiry would be to road test biogas bags due to their potential accessibility for most biogas owners (relatively low capital investment) as well as replicability in other places where biogas programs exist. The technical concept of bagging biogas for later consumption is proven, although not widely adopted and is, at the time of writing and as far as we are aware, undocumented in Tanzania. However, the concept of transporting the bagged biogas so that a different household can consume the surplus is relatively novel. Hence, we aimed to conduct a field trial of packaging biogas and consuming it as a cooking fuel elsewhere to enable Tanzanians to more fully understand and engage with the concept of packaged biogas. It was hoped that this would facilitate a much richer data set through the social-science methodology.

We procured eight biogas bags with $1m^3$ capacity from (B)energy in Germany[11]. These bags were connected onto existing digesters in Northern Tanzania. Experiences of using the bags to collect, store and distribute biogas were captured as part of the qualitative interviews outlined in Section 4 below. The biogas bag filling device has been designed by CREATIVenergie with input from the team at ECHO. This device allows gas to be automatically captured when there is a surplus, so that it is diverted to fill a biogas bag, rather than escaping to the atmosphere. The advantage of this method is that the owner of the biogas digester should not observe a reduction in availability of their own biogas supply, as we are only capturing biogas when there is a surplus. This system was field tested as part of this feasibility study.

We explored the technical viability of a low-cost biogas bottling method developed by LEAP as well as newly designed compression systems. The viability of bottling biogas is currently underexplored in the literature and in real-world settings. Attendance at a

[11] Refer to Sections 3.1.1 and 3.1.2 of this report for further discussion on biogas bags from a technical perspective, including safety.

conference at the University of Surrey also highlighted the sheer complexities and challenges of bottling biogas including compression of the biogas, size of containers *vis-a-vis* LPG canisters and price points. Examples of exploring the feasibility of bottling biogas in places such as Nigeria are yet to provide any concrete evidence. This justified our decision to explore bagging first.

The potential viability of using bagged biogas with biogas 'rice' cookers was also tested. This first took place in a controlled environment by our project partners at ECHO in Tanzania. The efficiency of cooking with a 'rice' cooker versus a single ring hob was assessed through practical trials of cooking a specific quantity of rice, a staple food in Tanzania, which gave a good indication of the increase in energy efficiency compared to ring burners. We then introduced these 'rice' cookers to four households at the end of Phase I field trials to gain user feedback (see Sections 2.2.3 on data collection and 3.1.5 for qualitative insights). For the communities we worked with it was the first-time people had seen or used biogas 'rice' cookers and so this helped to promote awareness and education around efficient cooking. Finally, 'rice' cookers were introduced as part of a 'Cook-Off', where we gathered community members to seek further feedback on their experiences of portable biogas plus cooking with a biogas 'rice' cooker. At this event a number of people were invited to cook the same meal using different fuels and/or kitchen appliances, including using bagged biogas with 'rice' cookers. The 'Cook-Off' also formed part of a dissemination event.

2.2 Social Science Methodology

This project sought to deepen understanding of the user experiences of biogas, and in particular portable biogas. There is already a documented literature around the failure of biogas for cooking (examples include low-income, high up-front costs, socio-cultural taboos around using excrement (both human and animal) as a cooking fuel, and failure of biogas systems). Yet, how do these examples fare if biogas can be transformed into a portable fuel that is accessible to a different consumer base and available at a cost on par with cooking fuels households currently use? We acknowledged that confirming the technical viability of packaging biogas into a portable form is not in itself enough to determine whether it is a cooking fuel that people will want to use. However, by exploring different distribution models and understanding user preferences for both supplying and consuming portable biogas, we set out to create a greater evidence base on which to assess the feasibility of promoting portable biogas for cooking. In order to explore this, a range of qualitative methods including semi-structured interviews, observations, cooking diaries and cooking demonstrations were implemented.

There were two phases of field trials:

- Phase I was a trial of peer-to-peer distribution with biogas suppliers and consumers who organised themselves to move gas from a household with a digester to another household with a biogas stove.

- Phase II was a trial of the milk-round distribution model using a different set of suppliers and consumers, with intermediaries transporting the biogas from the supplier to the consumers who cooked with biogas stoves.

For both phases biogas suppliers and consumer households were identified by our in-country partners at ECHO East Africa Impact Centre as follows.

2.2.1 Identification of 'Suppliers'

The biogas 'suppliers' were a mix of households who owned a domestic biogas digester. ECHO's team carried out a survey of biogas digesters in the Arusha region of which they had an existing relationship with the owners and created a long list of those households who had surplus biogas. Details of the biogas digesters sizing and design as well as the demographics of each household were collected. This data was used to select four households with domestic scale biogas digesters to act as suppliers for Phase I field trials, and two households with much larger digesters (approx. 16m^3) for Phase II. In addition, two intermediaries were identified as 'distributers' for Phase II whereby they would collect full biogas bags from suppliers and transport them directly to consumer homes. The intermediaries where identified by ECHO and were individuals with whom they had a pre-existing relationship and whom were familiar with biogas systems. They acted as independent distributers during the trial and provided feedback on the milk-round distribution model.

As part of Phase II, we had originally intended to approach a variety of potential distributers who already distribute/sell cooking fuels such as charcoal or LPG. We had also hoped to engage with a dairy farm micro-enterprise who use biogas to pasteurise milk as part of their business. However, due to growing concerns around COVID-19 in February 2020 this final part of the trial had to be suspended.

2.2.2 Identification of 'consumers'

These households were selected based on a range of criteria including their proximity to suppliers and the existing cooking fuel used. For example, the team ensured that there were consumers in the field trial who had no pre-existing access to LPG and those who did. Four households were selected for the Phase I peer-to-peer distribution trials, with one biogas producer household directly supplying one consumer household. A further four households were identified as biogas consumers for the Phase II milk-round distribution trial.

2.2.3 Data Collection Methodology

In both phases of the field trials, data was collected over a three-week period.

Once suppliers, (distributers) and consumers were identified, our in-country team visited and provided relevant training and demonstrations. In the case of suppliers, biogas filling devices were installed on digesters, with each digester owner being supplied with two biogas bags (one of the bags could be filled with surplus gas, while the other bag was at a consumer's home being used to supply fuel). The biogas filling devices allow surplus biogas to be harvested from a digester, without interfering with the biogas owners supply. It was explained that suppliers/distributers would be responsible for filling, storing and distributing the bags. The logistics of distribution was organised between suppliers, distributers and consumers.

In the case of consumers, our team provided biogas stoves (gas ring burners procured from CAMARTEC) to enable households to cook with the fuel from the biogas bags. Our team provided demonstrations on how to store and connect the bags to the ring burners and then cook safely and efficiently. We did not introduce biogas 'rice' cookers at this point to avoid introducing too many new concepts and technologies at the same time.

Once all the equipment was in place, an initial set of observations/notes was captured by our in-country partner, ECHO East Africa Impact Centre, to gauge initial understanding, feelings and any apprehensions of project participants. These initial observations and notes, based on a set of prompts rather than formal interview questions, were recorded in note form alongside any reflections the team members may have had. This process was especially important when the biogas bags were connected onto the digester filling stations and demonstrated to households, alongside connecting the biogas bags to the ring burners with consumers. This also ensured that our team were ready to provide the right support and/or technical assistance to participants throughout the project. We also requested that consumer households recorded in a diary when they cooked with the biogas and what they cooked. A template for this had previously been produced and implemented by ECHO and CREATIVenergie in previous projects[12].

In both project phases, it was planned that the ECHO team would visit consumers and suppliers on a weekly basis during the three weeks field trials of each distribution model. We aimed for these visits to be as informal as possible and so the team had a set of prompt questions/topics to discuss with both 'suppliers' and 'consumers' to capture issues such as usability, acceptability, technical challenges and feedback on distribution. The weekly monitoring visits were also an opportunity for our team to write their own observations and reflections (e.g. whether they think bags are being utilised, who is interacting with technology etc.), provide technical support and even perhaps help with the completion of cooking diaries and clarify any gaps etc.

At the end of each three-week period, semi-structured interviews were conducted with each biogas 'supplier' and 'consumer' to understand desire to supply/demand for biogas, preferred distribution networks and socio-cultural acceptance of portable biogas.

[12] We anticipated that there may well be issues of literacy in some cases and where a household is illiterate and is unable to capture the information, the ECHO team asked additional questions and tried to capture some of this information retrospectively at the weekly meeting.

Separately our team carried out an assessment of the technical and practical feasibility of using biogas ‘rice’ cookers with biogas bags. Initially trials were carried out at ECHO’s courtyard to become familiar with this new way of cooking. Subsequently we introduced biogas ‘rice’ cookers to Phase I participants after their biogas bag trial. The consumers used the ‘rice’ cookers for a week and provided feedback. A ‘Cook-Off’ event was then held at the home of a biogas promoter within the community and attended by participants from Phase I as well as other community members. This provided an opportunity for real-time feedback on the different cooking technologies as well as providing an opportunity to ask questions and seek clarifications in relation to the initial peer-to-peer trial. At this event we invited participants to cook the same meal with different fuels, at the same time. Some people cooked on charcoal, others on firewood, some with biogas bags and stove ring and others using biogas bags with ‘rice’ cookers. The event was informal and provided a community dissemination opportunity, while allowing us to collect additional user-centric data.

Interview guides and cooking diary templates are included in Appendices A and B.

2.2.4 Data Recording

It was anticipated that all meetings and monitoring would be audio recorded with a Dictaphone (upon consent from participants). In the case where audio could not be captured, our in-country team wrote up all notes and observations and presented them as a word document in English. Thematic analysis was conducted on these documents.

Cooking diaries were pre-printed and provided to consumers at the start of the trial. Participants were guided on how to complete them throughout the three weeks. This data was manually analysed to look at cooking trends.

All semi-structured interviews conducted at the end of the 3-week trial periods were to be audio recorded and each interviewer printed out and took interview questions with them. They also took hand-written notes and observations that were written up into English. Audio transcripts were transcribed and translated from Swahili into English. ECHO’s team contributed to the initial analysis (especially in line with their extensive in-country knowledge/experience) to provide contextual evidence/conclusions and subsequent analysis was conducted using NVivo software to provide more objective/anonymised conclusions. This provided a richer dataset.

2.2.5 Ethics and Informed Consent

Prior to the trial beginning, we sought consent from all intended participants. We utilised existing templates that have previously been used by both ECHO and CREATIVenergie. All data has been anonymised.

2.3 Intellectual Property Rights

A number of prototypes were custom designed for this project in collaboration between CREATIVenergie and ECHO teams, and tested during field trials:

i. the surplus device to divert biogas from the digester to fill the biogas bags when a digester is full;
ii. a mechanism to pressurise the biogas bags in order to enable cooking;
iii. low-tech biogas compression technology;
iv. a low-cost biogas scrubbing device to remove CO_2 and H_2S from biogas;
v. digital technology to detect when there is a surplus of biogas and a mock-up of a trading application to enable to sale of biogas between suppliers and consumers.

The biogas bags procured from (B)energy are patented, but early discussions with (B)energy indicate they would be willing to form a license agreement for their manufacture in Africa. (B)energy patent claims relate to the innovative carrying/transportation straps and the thin porous inner membrane to enable the slow diffusion of CO_2 thereby enhancing the transported gas.

2.4 Assumptions Made

The qualitative methods implemented in this project were planned to be as informal as possible and to be led mostly by our research participants. There are several reasons for this. First, due to time, the research team believed it unfeasible to conduct semi-structured interviews every week which are often lengthy and take time to complete. The time it would take to conduct these interviews as well as transcribe, translate and analyse them would limit the overall time the team were able to interact with participants over the three-week period. We believed that our informal discussions, observations and interactions with several members of households would enhance the richness of data collected.

Second, the informal nature of our weekly monitoring discussions allowed participants to discuss the issues/topics that they feel were most relevant. Discussions could take any direction and was something we wanted to encourage. This allowed us to listen to what participants wanted to tell us and we could therefore alter the questions asked in the semi-structured interview to incorporate participants views throughout the trial period. It is also important to remember that our team were not only there to collect data but to also provide technical/logistical assistance with the biogas of which none of our trial's consumers had used before.

To that end, our recruitment of participants was based on a predefined set of assumptions by the project team. Due to time limitations, recruitment of participants that our in-country partners had pre-existing relationship with, was very important and ECHO acted as gatekeepers to gain access to households. Second, it was important for suppliers of bagged biogas to own a biogas digester and so therefore they already have extensive knowledge of biogas production and its existing benefits as a fuel. Although none of our participants had used portable biogas before, it is assumed that they have more knowledge of biogas over other potential participants.

3 Implementation & Findings: Technological Insights

In this section we consider each of the technical components of the system required for portable biogas to operate in practice. Working closely with the suppliers and consumers in the field trials, rapid prototyping was used in order to more fully understand the design requirements, constraints and the technological limitations. These insights will ultimately allow us to design an approach to portable biogas that is both appropriate and sustainable. Observations and findings are discussed throughout this section.

3.1.1 Safety

As part of the project we carried out a detailed safety assessment of the different steps required for low-pressure portable biogas. This included the following stages: filling bags with biogas at low-pressure, transporting biogas in low-pressure bags, storing biogas bags at low-pressure, using low-pressure biogas bags within a home to cook food. We also developed a methodology statement, detailing the safe operating procedure for each stage of the process. Safety documents are included in Appendix C.

3.1.2 Biogas Bags

Although biogas bags are already available in the open market, they are yet to be widely adopted. For our field trials eight biogas bags were procured from (B)energy. They are sold for 35.5 Euros each and hold 1m^3 of biogas. Two additional biogas bags manufactured by Shenzhen Puxin Technology Co. Ltd. were purchased and taken to Tanzanian by one of ECHO's interns. These biogas bag was used by ECHO's team for internal tests but not distributed to households within the community as it differed from the (B)energy design[13] and we wanted to ensure all suppliers and consumers used the same type of biogas bag for a more standardised approach and enabling comparison of their experiences.

Figure 3-1 Fixing a (B)energy biogas bag that got a puncture during the field trials

The (B)energy biogas bags consisted of two layers: a thin gas tight inner membrane, and a more robust outer layer to protect the bag. Despite this, the bags were easy to damage, and this occurred a number of times throughout the short three-week trial periods. Repairing holes in (B)energy biogas bags was difficult due to the materials from which they were made. The biogas bag liner was made of polyethylene, which is difficult to repair due to its low surface energy. This does not facilitate proper wetting and spreading of adhesive onto the polyethylene surface. Furthermore, polyethylene is not porous and therefore does not lend itself to mechanical surface

[13] For reference when looking at photos throughout this report please note that the (B)energy bags used for field trials with suppliers and consumers are white and the Shenzhen Puxin bags used for internal testing are blue. They also differ in construction materials and shape.

attachment (where adhesive to the surface is through mechanical attachment between cavities). Figure 3-1 shows an attempted repair made by the project team during the field trials. Specialist repair patches are required, which are not readily available in-country, and therefore must be supplied with the biogas bags. Long-term the ease with which damage occurs and the difficulties in repairing the (B)energy bags locally could render them less attractive. In order to address the challenge around biogas bag repairability and robustness, ECHO's team prototyped the manufacturing of biogas bags in Tanzania from thick PVC, the type of material used for curtain sided HGV trucks. These early stage prototype biogas bags were considered to be much more robust, and so less likely to sustain damage. Although more expensive to manufacture they were easy to repair (e.g. using readily available patches/plastic welding). Other materials, such as EPDM and HDPE are also being considered for future prototyping.

3.1.3 Diverting Surplus into Biogas Bags

There were not any appropriate commercially available devices to capture the surplus biogas from a digester and transfer it into the biogas bags in an appropriate way for the context of our field trials. Therefore we designed a device to extract biogas from a digester only when there is a surplus of biogas available. As already mentioned, the biogas bags used were $1m^3$ in volume, a significant quantity relative to the gas storage capacity of a domestic digester. For example, a typical $6m^3$ tubular digester (like that pictured in Figure 3-2) would have approximately $4m^3$ of slurry and $2m^3$ of gas storage. Extracting $1m^3$ of gas from a biogas digester in one go, to fill a bag, would significantly affect the household directly consuming biogas from the digester. Yet we know from our previous work, that biogas digesters continually produce gas and there are times during a 24-hour period when storage capacity is reached, and gas is automatically vented to the atmosphere. There is potential to utilise a greater quantity of biogas if storage capacity is expanded, e.g. through diverting biogas into bags at an appropriate rate that does not disrupt the supply for direct consumers.

Figure 3-2 A CREATIVenergie Expanding Bag Biogas Digester ($6m^3$), Tanzania

CREATIVenergie previously lead an international consortium, including ECHO, to design a remote monitoring system for biogas digesters. Having gone through a number of iterations, Smart Biogas[14] monitors provide data from which we have noted important observations over several years. Biogas digesters are designed to allow gas to be vented into the atmosphere when there is an over pressurisation of the system, in order to avoid explosions. Therefore, when the maximum pressure capacity of a particular digester is

[14] Smart Biogas is being commercialised by Connected Energy Technologies Ltd, a spin-out company formed following the conclusion of the Energy Catalyst project lead by CREATIVenergie. See https://www.connectedenergy.net/smart-biogas

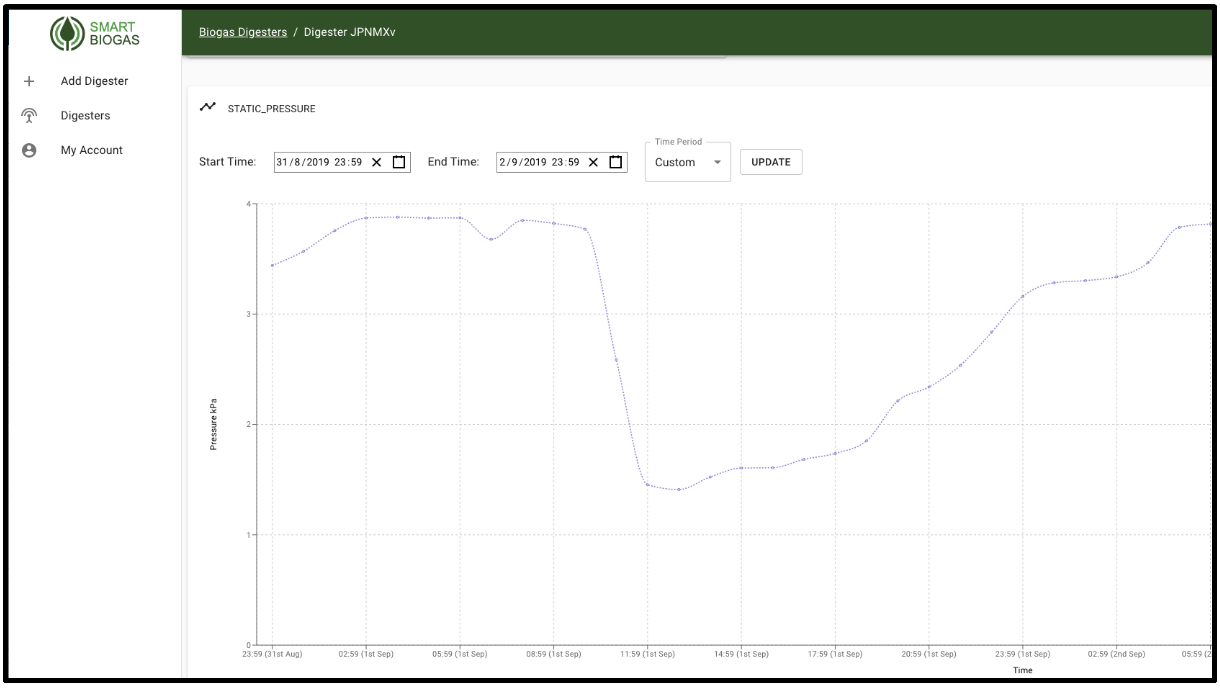

Figure 3-3 A screenshot of our Smart Biogas portal. The areas where the pressure plateaus indicate where biogas is being vented to the atmosphere; there is a surplus of biogas being generated, which is currently being lost.

reached, biogas is lost. Figure 3-3 shows pressure data for a biogas digester monitored through Smart Biogas. We know that pressure increases within the digester as biogas is generated and decreases whilst the fuel is used for cooking. A plateau at high pressure indicates that the maximum capacity of the digester has been reached, yet we know that the digestion process does not pause or stop. Therefore, during such periods, all new biogas generated is vented to the atmosphere, which means valuable energy supplies are wasted and also contributes to greenhouse gas emissions. It is not uncommon to see this pattern in when analysing monitoring data. In order to make use of fuel that would otherwise be lost (wasted), without negatively affecting supply to the household, biogas should be diverted into external storage (bags/bottles/canisters) during the period of high-pressure plateau.

In order to collect the surplus biogas, a device was custom designed to be placed between, and connected to both, a biogas digester and a biogas bag. The surplus device releases biogas from into a biogas bag when the pressure in the digester is greater than a certain threshold. This threshold pressure is set during installation of the surplus device to be just below the maximum pressure of each digester. This approach allows the collection of biogas without interfering with the owner's supply. The surplus device was designed to be simple and low-cost (affordable), in order to maximise future roll-out in low-resource settings.

Figure 3-4 illustrates how the surplus device works. The water height H determines the pressure at which biogas is channelled into the biogas bag, a value that must be pre-set for each specific digester design. If it is not already known, it can be determined by monitoring the pressure of the digester until the peak is reached (maximum capacity) and the water height then calculated from the equation $H=0.95P_{peak}/\rho g$ where ρ is the density of water, and the multiplication factor, 0.95, is to ensure the pressure (P) is captured into the biogas bag just before the peak is reached. This is because at the peak, biogas would escape to the atmosphere via the digester's in-built pressure release mechanism. Whenever the pressure of the biogas digester becomes greater than the specified pressure for the surplus device, biogas will bubble through and be captured within the biogas bag.

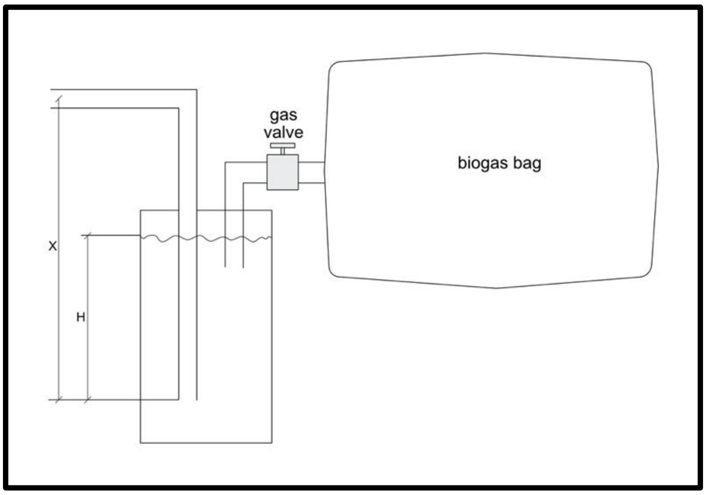

Figure 3-4 Technical Drawing of the Biogas Surplus Device

We know that there is moisture in biogas that condenses in the surplus device and therefore, over time, the water level H, and consequently the threshold pressure, increases gradually. In order to counteract this problem an overflow mechanism can be added to the surplus device, controlled by a float-valve which opens when the water level is too high, ensuring that the threshold pressure remains constant.

Another practical issue that emerged during prototyping was that if the biogas bag was not immediately removed once full, there were occasions when the pressure in the bag began to push the water out of the surplus device and back into the biogas digester. This occurred when the pressure in the biogas bag was greater than the biogas digester. For example when the bag is full and someone simultaneously consumes biogas directly from their digester, reducing its pressure. During this scenario water would be pushed back into the biogas digester along the tube between the digester and the surplus device, hence emptying the chamber and rendering the surplus device ineffective. The surplus device would then need to be refilled with water manually.

Consequently, the gas inlet pipe on the surplus device (connecting it to the digester) needs to have a height X which is equal to the equivalent maximum pressure differential that will occur. This is usually approximately 2xH for expanding bag digesters[15]. Calculating pipe length X for each biogas digester solves the problem of water overflowing requiring manual refilling. Now, when the pressure of the digester falls below the pressure of the filled biogas bag, water pushes up the inlet tube, equalising the pressure difference between the digester and the bag, yet is not lost back into the digester because the inlet tube is long enough to contain the water. We trialled this surplus device during both phases of the project's field trials and it performed satisfactorily.

Finally, another issue was identified when extracting biogas from digesters operating at a high pressure (normally dome type digesters). Our initial prototyping identified the need

[15] CREATIVenergie adapted the expanding bag digester design to increase its affordability and replicability without compromising quality. They have been working with ECHO since 2015 to disseminate this design as well as collaboratively revise and improve the materials and construction process.

to automatically stop the process of filling a biogas bag in order to prevent the biogas bags becoming over pressurised. Potential solutions to this problem include:

1. Additional pressure release mechanism between the biogas bag and the surplus device, which could use a similar principle as the surplus device, but vent to the atmosphere rather than a biogas bag. It would have a height H greater than that of the surplus device in order to prevent escape of gas under normal operation;
2. Have a mechanism before the surplus device that cuts off the flow of gas to the surplus device when the pressure is greater than a threshold value that exceeds the safe working pressure of a biogas bag;
3. To use a pressure release valve. Commercially available valves for the required relief thresholds tend to be prohibitively expensive. A simple spring-based valve could be 3D printed and potentially made with a workshop scale injection moulding machine. Indeed, a bespoke simple inline pressure release valve could also replace the current surplus device used in the field trials, allowing the biogas to be diverted into the portable bag without relying on water[16].

Figure 3-5 shows an annotated sketchbook drawing of the process of filling two biogas bags from the same digester (Phase II trials) and Figure 3-6 shows the surplus device installed at a supplier household in Northern Tanzania as part of the field trials. We designed the surplus device to be made from readily available parts to maximise the affordability and ease of maintenance. It proved to work well for expanding bag biogas digesters where the operating pressure is significantly less than the maximum working pressure of the portable biogas bags. However, for high pressure digesters (e.g. dome digesters that have historically dominated dissemination programmes in Tanzania), we recommended that inline pressure relief valves are used, as discussed above. Pressure release valves can also be used in scenarios where multiple bags are being filled from one digester to ensure biogas bags are filled sequentially from large digesters for milk round distribution.

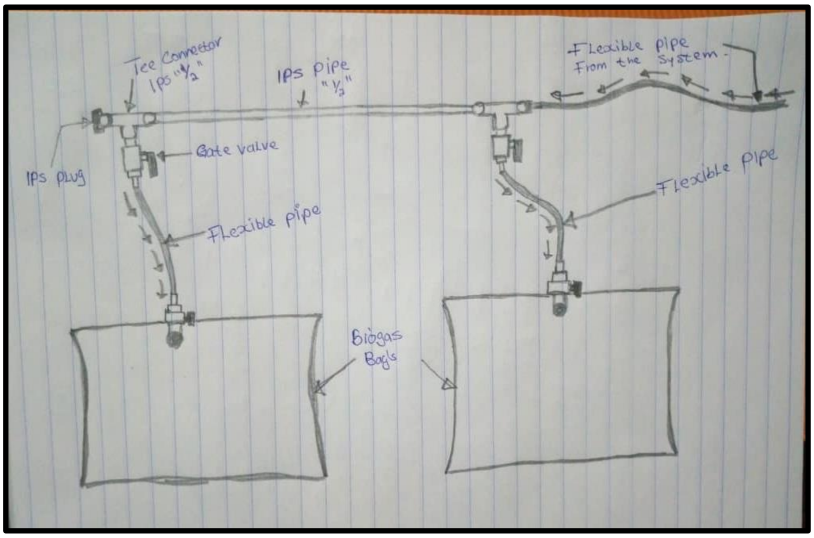

Figure 3-5 Sketchbook drawing of designs to fill two biogas bags from the same digester

[16] Further exploration, prototyping and testing of this concept will be continued by CREATIVenergie and ECHO as a sub-section of another project, Smart Energy Exchange Network, funded by Innovate UK's Energy Catalyst (working title Bitesize Energy Exchange). Design files will be made available when testing is complete.

We found that the four (6m³) digesters in Phase I of the trial each took between 2-4 days to fill a 1m³ biogas bag with surplus biogas via our surplus device[17]. This provides an indication that there is approximately a surplus of between 250-500 litres of biogas produced per day by each of these digesters. It should be noted that these households were selected to be part of the study because it was known they did have a surplus, and this is not necessarily indicative of all biogas digesters. In order to fully assess the market opportunity a much wider data set is required. We are in the process of installing monitors on a larger number of biogas digesters in Tanzania and Uganda as part of our current Energy Catalyst project and hope to have a better understanding of the prevalence of surplus in the coming months.

Figure 3-6 A biogas bag (left) and the device (centre) designed to fill the bag with biogas when surplus is generated by a digester (our of picture right).

3.1.4 Transportation of Biogas

Biogas bags are light in weight (~4.5kg), but they are large and awkward to transport. This creates a challenge around bulk distribution of filled biogas bags (e.g. in the milk round distribution). Even transporting biogas bags on the roof of a car (see Figure 3-7) is not very practical or cost effective over significant distances. Regular transportation also increases risk of damage to the bags.

Figure 3-7 A biogas bag full of fuel being strapped to the roof of a vehicle for transportation during the field trials in Tanzania

Transportation of the compressed biogas in cylinders (see Sections 0 and 3.3 below for discussion on compression) was much simpler. Although much heavier than biogas bags (~12 kg) the cylinders could be carried on your back or a number of them could be stacked and transported on or in a vehicle (e.g. a motorbike or truck). Being made from steel, they are also much more robust. However, the low volume of biogas to container weight ratio is an issue and the use of other lower density materials (e.g.

[17] In Phase II there was one dome digester that operated at high pressures and the surplus device was not suitable. Therefore, the biogas bags were filled directly from the digester in a couple of hours.

HDPE) for the manufacture of a new way to package biogas, could make this approach more usable for low-pressure compression.

3.1.5 Pressurising Biogas Bags for Cooking

The biogas bag is relatively lightweight and can be transported on your back, although bulky. However, in order for a consumer to use the biogas, it needs to be pressurised to a minimum threshold pressure in order to work with a biogas stove or rice cooker. The gas pressures required for biogas stoves and rice cookers to operate is generally around 5-20mbar, depending on the specific appliance. In order to achieve this pressure, one very simple approach is to put weight on the biogas bag. Figure 3-8 and Figure 3-9 show examples of bricks and sacks of sand being used respectively for this purpose. From a user perspective, in the initial trials of the system, it was clear that using bricks or sand bags in this manner was not considered ideal because they would sometimes fall off during cooking, the rough edges of the bricks and/or other weights that people had available could cause damage to the biogas bags. It also meant that there was not consistency across consumer households (different people would put different amount of weight on). The pressure on the bag was also not consistent, it did not work well and burning efficiency was not optimised.

Figure 3-8 Biogas bag weighted with bricks to provide pressure

Figure 3-9 Harold, from ECHO, filling a sack with sand to provide pressure on a biogas bag during early stages of the project.

In light of this every appliance should be fitted with a pressure regulator and the project team therefore designed a simple system to apply a consistent force to the biogas bags, shown in Figure 3-10. The elastic straps enable the frame to put a consistent pressure on the biogas bag. This is the design that was used for this small trial, however, during the trial we identified issues with this design (see Section 4 for discussion on user feedback on the pressurisation of the biogas bags).

Figure 3-10 Custom designed weighting frame used during portable biogas trials to provide a consistent gas pressure output suitable for cooking.

A more user-friendly approach is to use a gas pump to pressurise the biogas, powered by a small solar panel. In order to prototype this idea and get user feedback we managed to source a suitable off the shelf adjustable pressurisation pump (Figure 3-11), which was able to achieve the flows and pressures required to run biogas appliances. From a user perspective, the use of this pump made the whole experience of using bagged biogas much simpler, especially when it came to replacing an empty biogas bag with a full one (a process which needed to be done every 2-3 days). The user only has to connect the bag to a connector outside the property to make use of the gas, compared to the weighted frame system which requires a lot more effort to attach or remove a biogas bag. The pump can be combined with a simple control system to enable automatic pressurisation when the cooker is turned on, although this was beyond the scope of this project. The pump used as part of this trial was AC powered through an inverter, but to make this more suitable for use in off-grid locations, an equivalent DC solar powered option would need to be identified.

Figure 3-11 Low powered gas pressurisation pump which attaches to the biogas bags and increases the pressure for use in biogas appliances.

Another approach to pressurisation which was developed during this study is shown in sketches in Figure 3-12. This mechanism is designed to hang the biogas bag on the wall outside the kitchen. As the gas is consumed, the mass causes the dowel to rotate. The two dowels then effectively squeeze the bag and sustain a constant pressure throughout cooking. The pressure can be varied by changing the mass of the weight and the gap

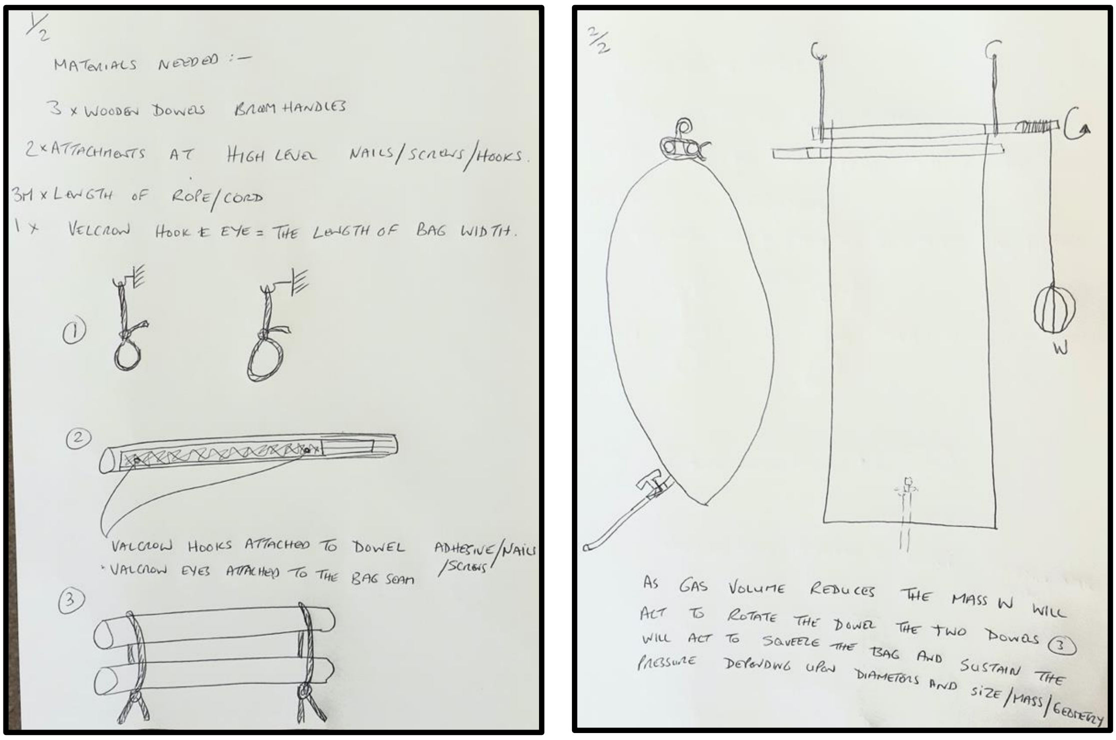

Figure 3-12 Sketches showing the design of the hanging compression system, an affordable and appropriate way of achieving a consistent flow of gas to the cooking appliance.

between the dowels. This is a simple and appropriate approach for off-grid communities and does not require solar power.

3.1.6 Biogas Stoves and 'Rice' Cookers

Ring burners were procured and installed in each of the consumer households. These stoves are widely available and are similar to those purchased by people who cook with gas in LPG canisters. LPG stoves can in fact be adapted by removing pressure nozzles and optimising the air mixing. In order to connect such ring burners to a biogas supply (both directly supplied by a digester or portable. biogas bags) it is necessary to provide a barbed connector and valve outside the household's kitchen but close to the area where cooking will take place, in order to minimise pressure loss in the supply line.

ECHO's team distributed the stoves to the consumer households and set up the equipment for the PHASE I trial. Equipment was later collected back again to distribute to the Phase II consumers. Four biogas 'rice' cookers were procured; they are not common in Tanzania. Discussion on user experiences of cooking with portable biogas using both ring burner stoves and 'rice' cookers is given in Section 4.3 below.

In a controlled trial, we demonstrated that cooking with biogas 'rice' cookers was more energy efficient than cooking with biogas and ring burner stoves. Cooking 1kg of rice with a measured amount of water (~2 litres) in the 'rice' cooker consumed approximately half the amount of biogas compared to using a biogas ring burner (approximately 250 litres of biogas with a biogas 'rice' cooker).

However, there were challenges using the biogas 'rice' cookers with portable biogas. One of the main challenges with biogas 'rice' cookers currently on the market for cooking with portable biogas, is that they did not come fitted with a gas pressure regulator valve and therefore the only way to control the rate of gas flow was directly from the biogas bag pressure/cylinder regulator. This was found to be a not very user-friendly process. Specifically, the flame could easily become too high or too low resulting in efficiency loses.

Figure 3-13 Cooking with compressed biogas and a biogas 'rice' cooker during field trials in Tanzania

3.2 Biogas Compression

Compressing biogas into canisters seemed like a logical next step after trialling biogas bags. Indeed, many of the households commented on challenges of using the biogas bags including transportation, storage and robustness (see discussion in Section 4 below). Therefore, in this project we explored some important aspects of the feasibility of compressing biogas for transportation.

Biogas generated by small domestic digesters using animal manure consists of mainly methane (~50-70%) and carbon dioxide (~30-40%) with a small amount of impurities including nitrogen, water vapour, hydrogen sulphide and traces of other volatile organic gases. Compressing biogas requires a considerable amount of energy, it does not liquify as LPG. To store an equivalent amount of gas as an LPG cylinder in a similar volume requires biogas to be stored under elevated pressure, which introduces some significant safety risks and concerns and was beyond the scope of this project.

An early stage biogas CNG compression project in Kenya was visited and the personnel were interviewed. The company reported three main challenges around usability, transportation and power supply. Users could not easily collect and maneuverer the cylinders themselves, as they can with LPG, and therefore a delivery-based business model is necessary. The weight also caused significant challenge in transportation of the cylinders (around 60Kg) and the number of people required to safely load the cylinders on and off a truck. The interviewees shared how one day they had a consumer who lived on a third floor and it was necessary to have 2 to 3 people to transport the cylinder to the kitchen, demonstrating how impractical that system is for a consumable product with a regular turnover. Another key challenge highlighted was that the compression system had high power demands to pressurise and liquify the biogas. Concerns were also raised over the cost-benefit analysis, of running a delivery service, especially when comparing this with regions already served with LPG.

In this project we took a different approach, asking the question: could we store sufficient biogas at low pressure in a transportable form factor, to make it possible to cook a households main meal for a similar number of days to a bucket of charcoal? In other words, can we offer something which is cost competitive with charcoal, is more convenient and cleaner to use. Essentially we were looking for a solution which sits between charcoal or fuel wood and LPG, a similar place to a biogas bag, but with greater quantities of biogas in a much more robust and portable container.

3.2.1 Biogas Compression Trials

Through our interviews, it was clear that the storage unit would need to be transportable on the back of a small motor bike and of a weight which was safe to carry on your back (not more than 20% of a person's total body weight). An average person weighs about 60kg, so at an absolute maximum the container, when filled with compressed biogas, should not be more than 12kg.

From our risk assessment of low-pressure compression, it was indicated not to use LPG cylinders for the storage of compressed biogas for the follow reasons. Firstly, LPG cylinders are normally owned and maintained by the supplying company, and therefore should not be used for other purposes. Secondly, LPG cylinders have a particular form factor that people associate with LPG gas. Hence, to store another type of gas in the same type of cylinder could lead to confusion. For example, LPG users trying to use compressed biogas on their LPG stove without modifications, or more dangerously, biogas users attempting to use LPG gas with their biogas stoves. Biogas contains H_2S which, unless the biogas is cleaned, will result in corrosion on the inside of the pressure cylinders and eventually catastrophic failure; it is essential to find appropriate and safe ways to store compressed biogas.

Bearing in mind the weight and material constraints, 10 litres steel containers, with an empty weight of 5.4kg were identified for the Tanzania trial. The steel cylinders were coated on the inside to ensure that they were not corroded by the presence of H_2S. These containers had a safe working pressure of 15 Bar of biogas, and therefore could store approximately 300 litres of biogas at ambient temperature. The cylinders were painted to BS4800 Yellow Ochre 08C 35 to denote that they were gas cylinders. This design of cylinder provided a good balance between pressure capacity and weight. The equipment used for the compression trials is shown in Figure 3-14.

Figure 3-14 Equipment for testing the biogas compression system including 2 steel coated cylinders painted yellow and a biogas 'rice' cooker to their left

The project initially considered several other approaches to the pressurisation (compression) of biogas. Observations are provided in the following sub-sections.

3.2.2 Hand Pumps

The first approach to compression we explored was the modification of existing bicycle pumps. Two types of pump were trialled: stirrup type bicycle pump purchased in the UK but manufactured in China, and a bicycle pump purchased in Arusha. The pumps were modified by removing the one-way O ring seal contained within the plunger and also by installing a ¼" bsp threaded non-return valve in the handle for the gas inlet. Whilst the pumps were able to pump high pressures, the effort and time to use these handpumps was considerable and they became very hot. The team concluded that although this process worked for a laboratory demonstration, this was not an appropriate approach to pursue for potential scale up, due to the time and effort required to pressurise the biogas and the reduced robustness of the bicycle pump (after modification).

Subsequently, a bespoke biogas handpump was designed and prototyped (see Figure 3-15). A double acting 50mm diameter with 200mm stroke pneumatic cylinder (Martin Air) coupled with four non-return valves worked well and was robust. At low-pressure progress was fine but as the pressure increased much more effort was required and just over 5 Bar was achieved. A single acting longer stroke cylinder and smaller diameter, possibly 30mm, would enable higher pressures to be achieved possibly up to 10 or 12 Bar with improved ergonomics, but again this would be with some considerable physical effort. Thoughts were that this type of handpump could be attached to a bicycle or maybe a motorcycle and driven with a suitable mechanism as legs and engines are more powerful than arms. We considered the pump design to be robust and appropriate. If it could be improved to meet the pressurisation requirements it may be suitable for use in remote settings for peer-to-peer sharing of biogas, although end user testing would be required.

Figure 3-15 A bespoke biogas handpump designed and prototyped during this project being tested in Tanzania

3.2.3 The LEAP Biogas Compression System

A member of CREATIVenergie's team went on a site visit to see a working LEAP biogas compression system in the UK. The approach uses a modified Danfoss compressor along with standard air fittings. The system works as follows: when biogas is released from the digester it goes into a temporary storage floating dome holder. When the level of gas in the holder rises above a threshold this triggers the pumping system to start via a mechanical switch. The gas in the storage holder is then compressed. The pump compresses the biogas to around 20 Bar. It enables surplus biogas to be stored. The compression system runs on solar panels. It includes de-sulphuring equipment to remove H_2S from the biogas. The compression system is primarily designed for local storage; however, the approach lends itself well to capturing and storing surplus biogas as it is created.

The technology is appropriate for a Sub-Saharan African context because the individual parts are readily available in the local supply chains and it is easily maintainable and repairable. However, the capital cost is high compared to low-pressure storage and significantly higher than the cost of a household biogas digester. Furthermore, it would add a high degree of complexity to a relatively simple digester system. Our project partner ECHO, based on their experience in the sector, suggested that the LEAP technology would not be appropriate for small-scale household digesters and were keen to trial more affordable compression technology. In light of this, the project initially considered the hand pump technology (described in Section 3.2.2 above). Subsequently, factoring in the need to maximise the amount of energy in a distributed package of biogas, we developed a prototype of an appropriate and affordable approach to upgrading and compressing biogas. In the future there is potential for the LEAP technology to be combined with the upgrading technology we developed, to compress the gas to an even higher pressure if required (e.g. for transportation).

3.2.4 Cooking with Compressed Biogas

Biogas was compressed from biogas bags into the cylinders and a meal (rice, veg and beans) was cooked with the compressed biogas (see Figure 3-13). Our practical trials showed that although we could cook a meal with compressed biogas, one day's worth of gas would be inadequate from a user perspective and increasing the number of cylinders would lead to a unit which was too heavy to be practical. In order to overcome this particular challenge, the project:

i. considered ways to upgrade the biogas and remove the CO_2, which has been discussed;
ii. investigated alternative materials for the storing of the compressed biogas;
iii. began to consider how to increase the storage capacity of existing vessels.

3.3 Overcoming the Limitations: Making Low-Pressure Biogas Compression More Viable

3.3.1 Hydro-Compression and Upgrading System

The presence of CO_2 reduces the heating value of the biogas, which has a significant impact on the cooking power that a household gets from a $1m^3$ bag of portable biogas. CO_2 comprises around 30% of the total volume of biogas in the bag at room temperature. Therefore, removing it would have a significant impact on the feasibility of distributed biogas, especially considering the practical limit on the volume that can be transported. Increasing the amount of energy the consumer has for cooking by a third could mean that you have approximately one additional day's worth of cooking fuel in the portable package.

As part of the project we considered if there might be a viable and low-cost way to scrub the CO_2 from the biogas. A review of different approaches for scrubbing biogas has been conducted by Yang et al.[18]. Pressurised water scrubbing is the most commonly used method. Other methods include pressure swing adsorption, Amine Absorption and Membrane permeation. However, water scrubbing seemed the most viable and cost-effective approach for an off-grid setting. It takes advantage of the higher water solubility of CO_2 and H_2S compared to CH_4. Existing water scrubber systems tend to be costly and use specialised vessels and equipment. In this project we designed our own prototype using the principle of water scrubbing but simplified to make it more suitable for off-grid biogas cleaning, and for small-scale domestic digesters.

An initial prototype of the system was developed, and field trials showed the percentage methane in the biogas increases by over 10%. The approach is simple, and, in this project, we were able to demonstrate the principle. However, much more work is required to fully optimise the system. It is anticipated that much higher percentages of methane upgrading are possible.

Figure 3-16 below shows the configuration of the system diagrammatically. A venturi entrains biogas from a low-pressure bag into a stream of high pressure and high velocity water. A 50-Watt agricultural water pressurisation pump was used in this trial. As the

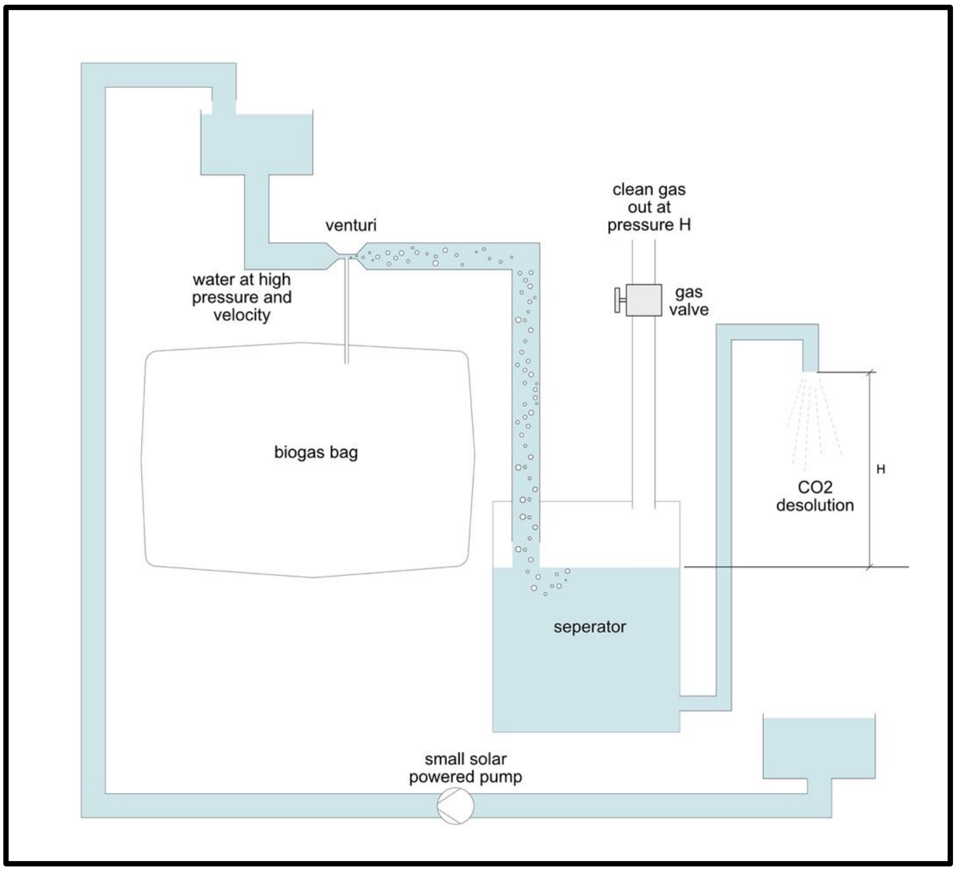

Figure 3-16 Design drawing for the hydro-compression and biogas upgrading system prototyped during this project for proof of concept tests in Tanzania

[18] Yang et al. (2014) Progress and perspectives in converting biogas to transportation fuels, Renewable and Sustainable Energy Reviews 40

biogas enters the water, many tiny bubbles are created with a high surface area. The size of the bubbles is a function of the diameter of the biogas-inlet tube (on the venturi), but in this initial proof of concept trial, this parameter was not optimised. The bubbles then travel along a pipe, and because of the high surface areas of many small bubbles and the residence time in the pipe plus the fact that CO_2 has a greater solubility in water than methane, CO_2 dissolves in the water. The high-pressure water causes the bubbles to compress, which aids the rate of absorption of the CO_2 in the water and the length of the tube determines the residence time and therefore the degree of absorption. When the water reaches the end of the tube it enters a separator vessel. This causes the biogas mixture, which is still in the bubble phase, to be released. The biogas then passes into the gas column and is released into the biogas storage vessel, which could be a biogas bag or a bottle/cylinder. The water, containing the dissolved CO_2, flows up the exit tube. The pressure of the upgraded biogas is proportional to the height of the water column, H, where the water exits the system. The water is then regenerated, removing the CO_2 from the water by aeration so that it can recycled in the system. What is interesting about this process is that the biogas undergoes quasi-isothermal compression, where the heat of compression is absorbed by the water and the pressurised biogas comes out at the same temperature as the water and is dehumidified. **Error! Reference source not found.** shows a sample of the initial data from this trial. The percentage methane (volume) in the gas was measured with a GX-6000 gas detector. The data indicates that the approach works and is able to remove both CO_2 and H_2S from the biogas, giving a gas with a higher methane content. There is a clear relationship, as would be expected, between residence time of the bubbles in the pipe and the percentage increase of methane in the biogas.

Flow Rate, water [litres/min]	CH_4 Before [%]	CH_4 After [%]	% upgrade	Length pipe [m]	Residence time [s]
7	60	70	14.29	4.5	4.89
7	60	65.5	8.40	4.5	4.89
6.85	60	67	10.45	4.5	4.99
7	60	80	25.00	7.2	7.82
7	60	82	26.83	7.2	7.82

Table 3-1 Summary of initial results from testing our hydro-compression and biogas upgrading process in Tanzania

The hydro-compression and biogas upgrading process has been far from optimised and there is a significant amount of work required to both fully understand the process and optimise it to maximise the methane content of the upgraded gas. For example, the venturi entrainment design can be optimised to achieve optimum flow rate of biogas and bubble size, the separator can be improved and the relationship between the different parameters needs to be better understood. Currently the biogas pressure is a function of the height of the outlet, H, however, some experimentation has indicated that a ram type system, similar to a ram pump, is able to create much higher pressures at much lower head heights. This could potentially provide a way to upgrade, dry and compress biogas in a single process.

There is an opportunity to design the system to achieve the same result with some different configurations which would be very simple to assemble and manufacture. Testing of these systems along with a cost benefit analysis of this system would be an area of further work.

The approach described is able to upgrade and compress biogas. It is simple and can be assembled with readily available components. An upgrading system of this nature is important for the long-term success of portable biogas - it increases the amount of energy within a biogas bag or cylinder, potentially by up to one third, improving user experience and making business models more viable.

Figure 3-17 A working prototype of our system to upgrade and compress biogas at ECHO's East Africa Impact Centre, Tanzania

3.3.2 *Alterative Materials for Compressed Biogas Storage*

Steel was not an ideal material for the transportation vessel due to the fact that it can be corroded by the H_2S in uncleaned biogas and its high weight to storage volume ratio. An alternative material that is more suitable for storing the compressed biogas might be HDPE. Commercial 200 litre cylinders were identified, however, these were designed to have much higher working pressures (~300 Bar) than is required for low-pressure compression and consequently they are very heavy (48kg). However, they are very affordable (each one costs around $7 from Alibaba). These particular cylinders would of course be too heavy for this application, however, should the market exist it would be possible to work with the manufacturers to develop a suitable vessel for our application. There are clear advantaged of HDPE: it is much lighter per m^3 of storage than steel; it is resistant against corrosion; it has a much lower price point per m^3 of storage; the manufacturing process is much quicker and easier to maintain quality, once it is set up.

Figure 3-18 Harold, from ECHO, visited a biogas compression company in Kenya where CNG cylinders are used to package and distribute the biogas.

Our team is committed to continuing to explore alternative ways to package biogas, making it a portable cooking fuel.

3.3.3 *Alternative Ways of Storing Biogas at Low-pressure*

The project began to explore ways to increase the amount of biogas stored in the same volume container using an adsorbed natural gas (ANG) technology, which is based on the use of an adsorbent with a high number of micropores to fix and accommodate the gas molecules. The high volume of micropores causes many molecules to be attracted to the surface of the adsorbent, resulting in a higher density than that of the gas phase in equilibrium. The result is that a higher storage capacity for the biogas is achievable with the same volume. A simple approach was explored using granular activated carbon, although developing this was beyond the scope of this project and would need to be developed in future work.

4 Findings: Qualitative Insights

4.1 Supply of Biogas Bags

Portable biogas, especially bagged biogas, is a relatively new concept including in rural Tanzania. There are very few examples of this in the region, except in Kenya. Even then, portable biogas has mainly been produced using industrial compression equipment rather than at the micro-level (community/household). It is unsurprising that our participants had never heard of portable biogas.

That being said, all suppliers of biogas in this project either owned or had extensive experience using a biogas digester and therefore the technical process of bagging biogas was described as a "relatively straightforward process" and "simple". In addition, most suppliers explained that they do produce surplus biogas but had been unable to do anything with it, until now. To that end, the process of bagging biogas was not seen as a task that took up additional time or resources and was something welcomed by suppliers. One supplier told us:

> *"I was used to this thing [filling the digester] and therefore filling the bags is not a problem…".*

As part of our interviews and informal discussions, we tried to speak to all people who were involved in the production of biogas and the filling of bags. It is not entirely clear from our data who has responsibility for filling these biogas bags. Phase I of our research determined that the production of biogas, and in turn the supply of portable biogas, is mostly a collective task completed by several people in a household (including children) but overall ownership of digesters and biogas bags would usually belong to the household head, in most cases, a man.

Despite it being relatively straightforward to fill bags, our data overwhelmingly found that seasonality greatly impacts the supply of biogas (regardless whether using bags or not). All suppliers explained how the weather affects the amount of time it takes to produce biogas and fill bags. One supplier stated:

> *"[the] time to fill the bags is relatively [ok] but it is greatly affected by the weather".*

These sentiments were echoed throughout the research period stating that both the cold weather and the rain limited their capacity to produce biogas. In the cold weather, it could take up to two days for the biogas bags to be full, but the warmer weather could take as little

Figure 4-1 Attaching a pipe to a biogas bag so that it can supply fuel for cooking

as two hours[19]. The seasonal variability in the supply of biogas may have long-term implications on its sustainability as a cooking fuel which will need to be addressed in order to scale up the production of biogas bags. The rains also impacted on distribution especially when biogas bags are collected and delivered on foot.

Another recurrent theme impacting on the supply, distribution and use of portable biogas is the size of the biogas bags which was seen as a potential drawback. The size of the bag (see Section 3.1.2) was considered by many as too large for a number of reasons. First, suppliers complained that despite its large size, the bag didn't hold much gas and so a bag would need to be refilled every two to three days[20]. These sentiments were echoed in the dissemination workshop where participants explained that the volume of the gas was small vis-à-vis the size of the bag and so the large size was somewhat negatively perceived.

At the same time, both suppliers and consumers were overwhelmingly in favour of storing portable biogas in a smaller apparatus, such as in containers similar to LPG. There were many reasons given for this. Some mentioned that smaller bags would mean that they would be less prone to damage and punctures and it is important to note that during this research all suppliers and consumers complained about leakage issues of biogas bags and that the bags were deflating over time which ultimately impacted on supply and use[21]. People mentioned that the storage of biogas should be in a hard container like LPG cannisters which would make the fuel more "robust" and improve the distribution process

Figure 4-2 Herry talking to a biogas consumer during field trials for portable biogas (left) and another biogas bag in a weighting frame at another consumer's garden (right).

[19] See Section 3.1.3/

[20] It is important to note that during the trial period, this frequency of filling bags every few days didn't seem to impact suppliers and their existing capacity to manage their digesters, however consideration may need to be given if the demand for bagged biogas increases.

[21] As explained in Section 3.1.2– punctures in the bags were difficult to fix without specialist repair patches. Consequently, peoples' frustration with biogas bags could be a result of the type of bag purchased for this research, which resulted in local attempts to fix the bags to be in vain.

(see Section 4.2 below)[22]. Mainly, a smaller apparatus to store portable biogas was preferred as it would be easier to store. Due to its current size, biogas bag equipment needs to be setup outside (see Figure 3-10, Figure 4-2 and Figure 4-3) and both suppliers and consumers complained about the large space this took up[23]. Suppliers mentioned that biogas bags need ample space and need to be closely monitored. One supplier stated:

> *"The storage [of bags] requires a large area for safety purposes. You have to ensure that there aren't any sharp objects [that] would pierce through the bags or rats that would chew away the bags".*

Equally, suppliers also mentioned that children could potentially damage the large bags and so there many ideas voiced to try and remedy this. Ideas included, a separate building/outhouse to store the bag equipment, hanging the bags up high against the wall, and even building something around the bag to protect it better. In turn, having biogas bags stored outside added to security concerns especially around the theft of equipment and so some people suggested a watchman or some form of security to protect the bags.

In terms of ownership of bags, as perhaps would be expected, the novel technology and approach of this research gained much interest and enthusiasm from participants. By the end of the trial period there was a consensus that suppliers should own the biogas bags and that they be responsible for filling and maintenance. It is important to note here, that in most cases the ownership of bags would fall to household heads, usually male.

The process of supplying portable bagged biogas is something that is considered as simple. Our data highlights that minimal technical assistance is needed, especially when suppliers already own biogas digesters and have experience producing biogas. Our data also shows that seasonality and the size of the bags impact on the supply of bagged biogas and will need to be given greater consideration when thinking about scaling up production and the sustainability of bagged biogas as a cooking fuel.

4.2 Distribution of Portable Biogas

4.2.1 Peer to Peer Distribution

In the peer-to-peer-distribution model, suppliers and consumers of portable biogas were located in the same community. As a general note, this model was perceived as positive throughout the research period and meant that suppliers and consumers knew each other and were able to maintain any pre-existing relationships. When asking both suppliers and

[22]However, contradictory to this, lengthy discussions at the workshop suggested that biogas bags were perceived as safer to use in comparison to LPG containers as "the bags don't explode" and so further investigation into the containerisation of biogas would prove timely to add to the evidence base on the safety of portable biogas.

[23] It is important to note that from a supplier perspective, space was not necessarily an issue during our trial period as they had assistance from the ECHO team who were able to find adequate space to set up the surplus device and bags and provide technical support and maintenance in case there were any challenges.

consumers about this model, one of the first things mentioned was that they knew each other well and were “friends”. The workshop appeared to confirm this because “you can’t do business without good relationships”.

Communication between suppliers and consumers as part of this model was mainly face-to-face but some did say they exchanged text messages. For example, one supplier explained that “we send a text message to confirm if the bag is over or not” as a way to ensure that another bag is ready to replace so the consumer is not without fuel. Upon further discussions, both suppliers and consumers stated that they would prefer either face-to-face or telephone communication. As one supplier mentioned “I don’t have to call her using my cell phone as she occasionally passes by our house”. Overall SMS was not preferred due to a preference for face-to-face communication. One supplier did mention that the use of WhatsApp would work well but this was mentioned in passing. However, it is unclear from our data specifically who is communicating with who. In terms of consumers, we spoke to all those who have financial power to buy fuel and most importantly use the biogas bags for cooking and so most of these were women. In terms of their communication with the supplier, we do not have much detail on those specific face-to-face meetings but do know that communication involves the person who is distributing/collecting the biogas bags, often the son of the supplier/consumer.

Our research found that the mode and frequency of communication as part of the peer-to-peer distribution model is very much related to the ownership of the biogas bag. We found that overall, suppliers of bagged biogas should own the bags and take responsibility of any assistance, maintenance and communication needed when in use by the consumer. However, it was undecided who should be responsible for distributing the biogas bags, full or empty, regardless of ownership. The workshop discussions alluded to a system in place like there is with LPG whereby the supplier own the bags and consumers exchange empty bags for full ones but there were still perceptions that suppliers of bags also be responsible for distribution because “the customer is king”.

As a result of being located in the same community, the distance between suppliers and consumers was approximately 100-200m meaning that transportation of bags was mainly done on foot. We found a mixed response to this method from both suppliers and consumers. As with the supply of bagged biogas, seasonality also affects the distribution of bagged biogas, especially when being distributed on foot. Often, heavy rain meant that distribution of bags would not take place therefore disrupting the availability and ultimate use of biogas. Some participants mentioned the use of a bicycle and/or motorbike, but the weather may also impact this distribution. At the same time the size of the bag limited the mode of transport that could be used making walking preferable. However, there was a sense of embarrassment at times due to the large size of the bag during distribution. One person explained that “if you walk in the street people look at you” and these sentiments were echoed throughout the research period where distributing the bags mainly on foot was considered “awkward” and a “challenge”.

As discussed above regarding the production and supply of bagged biogas, storing the biogas in a smaller apparatus is preferable by all, especially when distributing it on foot. One supplier said "[The bags] are just too big to be carried on someone's back" while others mentioned that "LPG is easier to carry" confirming that portable biogas should be smaller and more manageable to transport. When discussing the longer-term transport options of portable biogas, both supplier and consumers agreed during the workshop that they would be happy to walk maximum 15mins one way to collect a biogas bag if walking was the main mode of transport.

The mode of transportation used to distribute portable biogas and the person responsible for distribution/collection will impact on the price at which portable biogas is sold[24]. The data gathered from suppliers suggested that they would charge anywhere between 2,000-5,000TSH[25] (with 2,000-3,000TSH being the most common price) for a biogas bag[26]. However, suppliers mentioned that an additional 500-1,000TSH could potentially be added to that price if they were also responsible for distributing bags. This could imply a very high price for portable biogas, especially if bags are needed to be refilled every two to three days.

The division of labour and roles within the portable biogas value chain will also vary depending on the type of distribution network in place. For example, from this research, the peer-to-peer distribution network very much maintains traditional household and community roles which, may in turn impact on the supply of bagged biogas, the retail price of bagged biogas and even the consumption of it. For instance, our data highlighted that supply of bagged biogas was not always regularly available due to a variety of factors (seasonality being a major factor – please see Section 4.1 above). In this case, rather than seek bagged biogas from a different supplier, the peer-to-peer distribution network meant that consumers would simply go back to using their other fuels until bagged biogas became available again from their supplier who were neighbours and often friends. The distribution network in this case would ensure that community relationships were upheld even if it meant a lack of supply. For example, one consumer told us:

> *"We had a good relationship with the supplier, and he used to refill the gas on time. …. I would like it [distribution model] to remain as it is".*

At the same time, the peer-to-peer distribution network could affect the involvement of different people in the model and the formality of that involvement. For example, this research highlighted that often the son of the supplier/consumer acts as intermediaries and would often distribute full bags of biogas and collect empty bags to be refilled. There needs to be further discussions to better understand if the son, or younger family member

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[24] The data gathered as part of this research included informal discussions about willingness to pay for bagged biogas and the price people would be happy to sell/buy. As such, a full cost analysis would need to be conducted to extract the true cost implications of supplying and buying portable bagged biogas.

[25] Based on exchange rate of $1 = 2,134.42 TSH

[26] Clarification will also be needed over whether this cost truly reflects all costs including equipment, labour, maintenance, communication etc.

responsible for distributing/collecting bags would be viewed in a professional capacity in this role or would even profit financially from their tasks. The peer-to-peer distribution network in some ways accepts that it is not only the son's duty to distribute the bagged biogas to neighbours and friends but also to ensure that it is connected properly to the stove and bring back empty bags to be refilled. For example, one supplier told us:

> *"it is our son who helped take the bag to the consumer… the consumer has no experience of re-installing the bag. That is why she requested assistance".*

This in turn can impact the sustainability of the peer-to-peer distribution model.

The peer-to-peer distribution network is favourable in many circumstances and was echoed during Phase I. This can be explained due to the long-standing relationships within communities whereby there is a great deal of trust between supplier and consumer. The data we have suggests that people would prefer to communicate and deal with someone they already have some sort of relationship with but begs questions about capacity and saturation in the long term, the impact on these relationships if there are problems and reaching potential consumers beyond community boundaries.

4.2.2 Milk Round Distribution

Phase II of this research project aimed to further understand distribution routes of portable biogas through a 'milk-round distribution' whereby independent entrepreneurs or employers of small-scale businesses distribute portable biogas direct to consumer homes. The milk-round distribution as part of this project was only partially completed due to the impact of COVID-19 (see Section 4.5 below) and therefore the data presented in this section should be considered as emerging themes and not as solid conclusions about the viability or sustainability of this distribution model. As explained in the methodology, we spoke to suppliers of biogas who own larger biogas digesters compared to those in Phase I, we spoke to independent distributers who acted as intermediaries between suppliers and consumers, both transporting full biogas bags and collecting empty ones. We also engaged with consumers of bagged biogas in this phase to add depth to the data already collected on consumption of biogas bags but mainly to understand perceptions of distribution routes of portable biogas.

As uncovered in Phase I, main findings in Phase II found that seasonality and the size of the bags were the largest barriers when it came to distribution. Like in Phase I, we found that the cold weather and rains affected the supply of biogas and in turn the time it took to fill bags. We found that this had a greater impact on distribution in Phase II, especially when there is an intermediary involved in distributing bags. One distributer told that us that there was sometimes a delay in being able to collect the biogas bags as a result of supply and he had to make multiple trips to the supplier to eventually collect the full bags, ultimately increasing the time spent on this activity[27]. It was, however, the weather that

[27] Especially if distributers are also responsible for filling biogas bags

really impacted on the distribution of bags, especially when travelling on foot or by bicycle. One distributer told us that the weather is "not conducive" for distributing biogas bags which could be seen as a lost opportunity as there could be increased demand for portable biogas during the rains especially because people can't use firewood. At the same time, the poor weather also meant that distributing biogas bags on foot was increasingly difficult due to the narrow mud roads, making some areas hard to reach. The small narrow roads also made it difficult to transport the large bags especially when there are others on the road.

Like in Phase I, suppliers, distributers and consumers told us that the size of the bags were too big and would prefer a smaller container such as LPG cannisters. Our distributers said that smaller bags/containers to transport biogas meant they would be able to take more than one bag at a time supplying to more households.

Figure 4-3 Transporting a biogas bag by bicycle during Phase II Trials (left) and biogas bags being filled at one location with a large biogas digester as part of the milk-round distribution (right)

In terms of supply, the time it took to fill biogas bags was much quicker and this can most likely be attributed to the larger size of digester in comparison to those in Phase I. It is reasonable to suggest that when thinking about scaling up the production of portable biogas, a minimum requirement would be a digester size of at least 16m^3 so that:

i. supply does not interfere with household consumption if indeed household digesters are involved in the portable biogas value chain[28] and;
ii. it minimises disruption of demand even if the supply takes longer due to bad weather conditions.

[28] Especially if in these cases, the surplus biogas is needed by households for their own consumption.

It will be important to trial the supply and distribution of portable biogas from a large digester, perhaps located in an urban centre, to see if the disruptions of supply in this project fare any differently.

In terms of consumption, as in Phase I, consumers agreed that cooking with bagged biogas was fast, and simple and cooked foods on par with LPG. Challenges faced was that the bags depleted too fast. Consumers also emphasised a preference for milk-round distribution due to the novelty of an intermediary supplying fuel directly to their household.

However, we also know there will be additional cost implications as a result of the milk-round distribution. Suppliers in Phase II employed at least one person to feed the digester due to its larger size and if they are involved in the filling of biogas bags also, it will impact on the price of which full bags are sold. At the same time, this distribution model will include a charge for the distributer themselves for transporting the bags to and from consumers. We do not have much data on how much distributers would charge for distributing bagged biogas, but one distributer told us that it needs to be a price that "would keep me motivated". In line with what we found in Phase I, a minimum cost for transporting bags would likely be around the 1,000TSH mark depending on mode of transport. It is likely that the lower figures would represent the charge if distributers travelled on foot or bicycle. In addition, in line with challenges faced by consumers that bags depleted quickly, it would ultimately increase the frequency of distribution every 2-3 days which will need to include distribution costs. Despite not being able to collect all data on the milk-round distribution model, we know that there is a degree of separation between the supplier of portable biogas and the consumer so it can be assumed that the final retail price of bagged biogas would include costs such as labour, transportation, distribution etc. ECHO carried out an initial cost benefit analysis of this model, which is given in Section **Error! Reference source not found.**. However, more research is needed on the financial viability of this distribution model.

We also were unable to capture sufficient data on the ownership of bags during this part of the field trials. Various assumptions can be made based on the limited data we have. For example, distributers may own the biogas bags and pay suppliers for the supply of biogas and then charge consumers based on factors such as transport, fuel and profit. However, suppliers will need to own sufficient equipment to supply portable biogas and so therefore the price they charge distributers could be different compared to if they were supplying bags directly to consumers. As proposed in Phase I, the consumer could potentially lease the bags from suppliers/distributers like the LPG model. Further research is needed to determine ownership of equipment as part of this distribution model.

Finally, we were unable to further understand the gender and social inclusion implications as part of this distribution model. The two distributers we engaged with were both male and based on feedback on the size of the bags, the women we spoke to felt the bags were too big and at times awkward to move, especially when set up in the household for consumption. We need to understand whether the size of biogas bags would negatively impact women or other social groups from being distributers. It can be suggested that if women were involved in the distribution of portable biogas, it could be explored through existing community hubs such as markets places.

In short, there was enthusiasm about this distribution model, however, the supply of portable biogas through intermediaries alone have additional logistical and financial implications which may ultimately drive up the cost of portable biogas impacting on its sustainability. It is important to engage with businesses/industry who currently use biogas to further understand the sustainability of this distribution model.

4.3 Cooking with Portable Biogas

4.3.1 Current Cooking Habits

As expected, both suppliers and consumers explained that they use a mix of fuels and technologies to meet their everyday energy needs, including biogas (Figure 4-4 and Figure 4-5). Participants as part of this project typically used a mix of firewood, charcoal and LPG. The use of biogas as an everyday fuel as part of the current cooking fuel-mix is somewhat limited to those who have existing biogas digesters, but those who are already using biogas[29] are overwhelmingly in favour of using it as it is considered simple, easy and fast.

Figure 4-4 Cooking with fuel wood is a common practice across Sub-Saharan Africa

In line with the literature on stacking, cooking fuels used by people in this project vary depending on factors including cost, availability, seasonality, family size, and food cooked. Many of the discussions we had around current fuel discussed how much people pay for their fuel, how often and the limitations they face. As one consumer summed up to us:

[29] It is important to note that suppliers were already using biogas for cooking as part of their everyday energy needs. The views expressed by suppliers on cooking with biogas is based on current experience when derived from the digester and not using biogas bags.

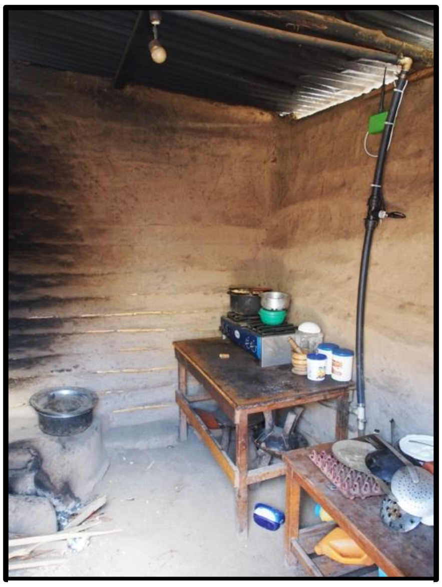

Figure 4-5 Evidence of fuel stacking in Tanzania: burning wood (left) and a double ring burner connected to a biogas digester (right)

> *"Scarcity of charcoal could be one of the challenges. Firewood pollutes the environment, it takes time for the biogas to light up because you have to exert pressure on the bag and the LPG is costly"*

In relation to foods cooked, one person also explained to use that:

> *"It depends with the type of food. There are foods that take longer to cook so the gas makes it easier as compared to when you use charcoal. Firewood is relevantly easier to use but it isn't too kind to some types of foods".*

In short, there are pros and cons of using each of these fuels rather than there being an overwhelming preference for one particular fuel.

Interestingly, some women (both suppliers and consumers) highlighted the importance of traditional biomass fuel (firewood and charcoal) to cook traditional foods. Examples include the preparation and cooking of Loshoro (a banana, maize meal and milk meal), traditionally made by the Maasai which requires it to be cooked in a large clay pot (Chungu) and must be cooked using firewood. Similarly, one woman explained to us:

> *"every morning, I use biogas when preparing tea for the family and subsequent meals. This is to say, we normally spend five hours on Biogas, daily. However, there are some African dishes such as Makande which will compel you to use charcoal as they take much time to prepare"*

The cooking of Makande (corn chaff) is a meal made of crushed maize and beans traditionally cooked by the Pare people but is commonly cooked by households in Northern Tanzania. In this instance, charcoal is needed for slow cook purposes and cooks would not consider using biogas (or LPG) for those meals. Similar thoughts were echoed when cooking 'hard' foods such as ugali or beans and some mentioned that the use of gas fuels when cooking these meals would deplete the resource faster. It is likely that these traditional meals could be cooked more efficiently using biogas and other 'modern' fuel sources (such as solar-electric cooking) saving time and money. More research is needed to understand why people continue to cook certain meals with biomass over other fuels.

4.3.2 Cooking with Bagged Biogas

On the whole, our consumers had a positive experience using bagged biogas to cook. Commonly, the bag would be attached to a single ring burner (Figure 4-6). People said it cooked food quickly, was easy to light, had a good flame, and was simple to use. Most people said that biogas could cook a wide range of foods including but not limited to; tea, vegetables, rice, stew, porridge and boiling water. It was observed that the use of biogas was particularly popular in the mornings to make breakfast and to make tea. One woman explained to us:

Figure 4-6 Cooking with a ring burner powered by biogas

"it is efficient especially in preparing breakfast for the children when they are going to school and also my youngest child takes his porridge on time".

Consumers also liked that cooking with the biogas bags saved them time to do other activities. One woman told us that she felt she could spend more time with her baby because she didn't need to spend so long tending to the fire. Consumers also compared the use of portable biogas with LPG and it was also a reason as to why they liked using it. People said they found no difference in cooking with LPG and bagged biogas and depending on the retail price, could be less expensive than LPG, although this was perhaps more out of an optimism rather than fact.

Despite the overall positivity of cooking with biogas bags, consumers did experience challenges with it. One of the biggest challenges was that the bags would run out of gas quickly meaning that it would need to be refilled every 2-3 days. Some mentioned that because of this, they would still prefer to use LPG as it lasts longer. There were also complaints that biogas damages existing pots and pans as a result of the high pressure exerted. This was something that both suppliers and consumers commented on, and would lead to additional cleaning or the purchase of new pots. There were also examples of the bags deflating as a result of punctures, holes etc. and also challenges around pressure in order to use the biogas bags (see 3.1.5 above for discussion on how we addressed this issue). One woman told us:

Figure 4-7 A double ring burner connected to a biogas supply with a pressure monitor on the biogas pipe (mounted left)

"It is cost effective and friendly to the environment. On the other hand, it takes time to squeeze the bag in order to exert pressure for the gas to come out so that becomes a challenge.".

Like suppliers, consumers would also prefer portable biogas in smaller apparatus to provide a more efficient cooking experience.

A final point about price. Consumers mentioned that they would be prepared to pay 1,000TSH per bag of biogas. From understanding current fuel habits and purchase costs, they would price it roughly the same, or just below, what they pay for either LPG or Charcoal on a 4-week basis. The workshop ignited some discussion on this issue with a consensus of 1,000TSH being too low and 3,000TSH being too high a price. An initial cost benefit analysis has been carried out, however, more research into the financial viability of portable biogas should be included in further research.

4.3.3 Use of 'Rice' Cookers

As part of this research, Phase I participants were provided with a biogas 'rice' cooker to test out and provide feedback after their three-week initial biogas bag trial. Induction included highlighting that the rice cooker can cook more than just rice. Our team started to refer to them as 'efficient cookers' in order to reduce confusion around this point. Data was gathered during semi-structured interviews after consumers had been using it for a period of one week. It was suggested that the 'rice' cookers were easy to turn on and it was able to boil water and milk for tea quite quickly compared to other stove tops. However, there was a strong preference for the single burner hob. This was due to one main reason; namely that, consumers didn't like the slow cook functionality of the 'rice' cooker. As one woman pointed out:

Figure 4-8 ECHO team testing the biogas 'rice cooker (far left) and weighting the biogas bag (right) prior to the field trials

> *"when I choose to use gas, it is because I need to cook fast and therefore prefer the stove more"*

and this was reiterated by all our consumers. Also, at the same time, there is a preference to see a strong flame which people associate with fast cooking. Our consumers didn't like the small flames with which they felt they could not control their cooking.

Figure 4-9 Herry (far right) demonstrating how to use the biogas 'rice' cooker

Data gathered on the 'rice' cookers at the workshop was more positive with participants stating that it was better than the stove hob, cooks nicely and lasts longer than the stove top. It did however, highlight the same concerns as above and also suggested that 'rice' cookers would be more suitable for smaller families or single people but not for those with larger families because more portions/dishes are needed to be prepared and you cannot use multiple pots with the rice cooker. Other concerns voiced included that it is unsuitable to cook foods such as maize, you could only cook one dish at a time, and you can't use multiple pots which is not convenient. More R&D is needed into biogas 'rice' cookers and whether other appliances could be used with portable biogas.

Overall, the use of bagged biogas is favourable and is likened to LPG which is considered a desirable cooking fuel. It is important to highlight that portable biogas may likely form an additional source of fuel so that consumers can meet their everyday energy needs as best they can. The extent to which bagged biogas will replace or overtake other fuel sources is yet to be determined.

4.4 Socio-Demographic Data

Factors such as gender, household hierarchy, and age are embedded within the biogas value chain (as with other fuels and technologies) and naturally impacts on the division of labour, ownership of assets and use of bagged biogas. As expected, heads of household take responsibility and ownership of biogas digesters and equipment but rely on the input from other family members (such as wives/ children) to feed and mix the digester to produce the biogas. At the same time, women of the household are responsible for using fuel (including bagged biogas) and technologies for cooking which is as expected.

Within these stereotypical norms, there are a couple of interesting aspects that have come out of this research. Not unsurprisingly, both suppliers and consumers of bagged biogas discussed the help of a family member, usually a son or younger member of the household, to fill, distribute and collect empty biogas bags. While not a new finding in itself, this creates a potential opportunity to involve younger members of society as active (paid?) participants of distributing portable biogas. As explained in Section 4.2 above, younger family members, often sons, are responsible for distributing bagged biogas to/from suppliers and it is common that this is a service provided free of charge, especially as part of the peer-to-peer distribution network where community hierarchy is important. It is also important to note that younger children (under the age of 18) are also involved in the filling and distribution of bags which poses broader questions around health & safety and risk assessment. At the same time, these same people can potentially provide technological maintenance and support to both suppliers and consumers of portable biogas enhancing its overall acceptance and sustainability. These services are essential within the portable biogas value chain and are opportunities to explore further how other community members interact with portable biogas.

Figure 4-10 A woman lighting a biogas stove during the field trials

It is also important to further assess the accessibility of portable biogas. As an example, it was mentioned by women that standing up while cooking is better because "you don't get burnt easily in case of an accident." This may seem generic enough, but it is important to understand how much this also applies to cooking with portable biogas and how people who perhaps have mobility issues (wheelchair users or those using walking sticks) can cook comfortably and efficiently using bagged biogas. These concerns also apply to the supply and distribution of portable biogas. At the same time, there were concerns over the size of the bag and its transportation, as well as it's storage in a household which may impact on a

Figure 4-11 Cook-Off participants discuss their experiences of cooking with biogas using both the biogas 'rice' cooker and ring stove (left) and share a meal together to taste the food they cooked (right).

person's ability to use portable biogas. Most women complained that the large biogas bag was awkward to carry hence the need for a son/family member to carry it for them. This also begs further questions around how elder people in households would utilise and maintain bagged biogas and if the space required to store bagged biogas would compromise those who have a disability or even limit their ability to sell it as an income generating activity.

Ultimately it is women and girls who use these fuels to cook. Feedback on use has been positive, especially in regard to fast cooking, but if portable biogas is a desirable fuel in the same category as LPG with a significant cost attachment, it will ultimately impact on a woman's spending power and ownership of the equipment (especially a biogas 'rice' cooker or bags). It is in these cases, that heads of households dictate when and how often these fuels are purchased and what they are used for.

Understanding the socio-demographics of the biogas value chain may in turn allow a more holistic model to be put in place whereby traditional community roles are accounted for and are of benefit to the sustainability of portable biogas, especially at the micro-enterprise and household level.

4.5 Limitations of our Approach to Portable Biogas

Methodologically, the COVID-19 pandemic significantly impacted on Phase II of our research. We were unable to reach all intended participants as part of the milk-round distribution model and we were unable to complete data collection, including the end of Phase II semi-structured interview. Therefore, the analysis provided in Section 4.2.2 above is based on the limited data we have available and is not a substantial overview of the potential viability of the distribution model. Further research, along with full cost-benefit and economic analysis should be conducted to unpack this further.

In terms of participants, the suppliers of bagged biogas that were interviewed as part of this research already owned biogas digesters and they have collectively been in use anywhere between 4-15 years. Most suppliers are very experienced in using and supplying biogas and therefore, this small piece of research has been able to go one step further to prove technical viability of portable biogas. However, when wanting to roll-out and eventually scale up the supply of portable biogas, consideration will need to be given to the technical assistance and maintenance that may be needed for digesters and bagging technology, especially at the household level using a peer-to-peer distribution model. The supply of portable biogas may well be better suited to those who already own digesters.

Field trials ran for a relatively short period. If trials ran throughout a year or more, it would be interesting to note the perspectives of both suppliers and consumers. For example, the problems encountered due to seasonality and weather during the trial period may pale when considering biogas production, filling of bags and transporting them over a full 12 months and perhaps longer periods of better weather.

The sample size as part of the qualitative data set is relatively small with a total of 14 participants. It is unlikely that a larger sample size would have derived different/contradictory findings, however it would perhaps confirm our current findings and provide clarification on points/issues raised by a limited number of participants.

One further limitation is that participants were provided with the technology and equipment for the duration of the project by our in-country partners, ECHO East Africa Impact Centre, and they provided ongoing support and maintenance if and when needed. While participants did not keep the biogas bag technology at the end of the project, this may have impacted on their perceptions of using the technology, which was overall, positive. There was also no financial buy-in from participants and so it is difficult to determine which distribution model participants would truly prefer. Perhaps if participants were asked to financially contribute towards the technology or fuel at the start of the project, this may provide a reflection on the financial viability of the distribution models used in this project.

5 How the Findings Advance the Solution

There were many issues associated with the uses of biogas bags that were highlighted. Up to now discussions around biogas bags have tended to focus on the positive aspects of them, but here we now have a better picture of the challenges with them. 1) User concerns, 2) Practical issues around transport and storage, 3) repairability of the bags, 4) Storage issues. Awareness of these issues and the context around them is essential to developing a sustainable solution. It enables us to focus our technical innovation efforts around the challenges that need to be overcome in order to make portable biogas a more viable option.

One particular aspect to highlight is around the use of bagged biogas - the user experience can be significantly improved by using a pressurisation pump, removing a lot of the complications around man-handling a full biogas bag into a pressurisation system, something which is even more difficult if you are elderly or disabled. Although this is simple, it potentially opens up the use of the technology to these groups that are sometimes more vulnerable/marginalised.

The study has highlighted the importance around biogas bag design. A lot of the work, e.g. by (B)energy, has been innovative in terms of the selection of materials, but we have highlighted the importance of repairability and maintenance of the bags when designing. Future biogas bag designs should take this into consideration. Indeed, as we begin to explore large scale trials of the technology this is something we need to actively tackle.

The study also has highlighted how important research into the container for transporting is. A lot of compression studies either look at high pressure CNG, or look at compressing into existing LPG canisters, but there is less work on ideal lightweight containers for low-pressure distribution. The need for work in this area is important.

The development and testing of a device to make use of surplus biogas and avoid interrupting the supplier's own biogas supply is an important advance. It allows suppliers to potentially have an additional income source from a resource they already own, but which they were not currently making full use of.

To date, upgrading biogas on small scale digesters is rarely considered. However, in this work we have developed an approach, which uses few moving parts and which can be made using readily available components and to a scale which is appropriate to relatively small digesters (e.g. ~16m3). This makes small-scale compression more viable.

The peer-to-peer distribution model has been highlighted as very promising and it is therefore important to further develop how this could be scaled, and its potential impact.

6 Practical Applications of Portable Biogas to the National Cooking Energy System

This project has been able to initially assess the technical viability of portable biogas as well provide community insights into different distribution models and use of portable biogas. The key finding that consumers compare portable biogas to that of LPG importantly suggests that portable biogas can be seen as desirable, aspirational and transformative. With the recent surge in LPG production by private investors, the viability of portable biogas offers an additional cooking fuel that is viewed in the same manner as LPG but is ultimately not derived from fossil fuels. It is timely that efforts are scaled up to further test the economic and financial viability of portable biogas and to include key stakeholders at the national level such as the Ministry of Energy, The Tanzania Renewable Energy Association (TAREA), and Tanzania Traditional Energy Development Organisation (TaTEDO).

To analyse costs of bagged biogas the project team used Life Cycle Costing Approach (LCCA). The approach enabled us to make recommendations on the business models that were tested during the project implementation. Life cycle costing, or whole-life costing, is the process of estimating how much money you will spend on an asset over the course of its useful life. Whole-life costing covers an asset's costs from the time you purchase it to the time you get rid of it.

During the project we tested two business models namely peer-to-peer and milk-round distribution of portable biogas. This section discusses and analyses various components of costs identified by the project participants and highlights some recommendations.

6.1 Cost-Benefit Analysis of Peer-to-Peer Portable Biogas Distribution

As already discussed, the peer-to-peer distribution of portable biogas engaged households with biogas digesters generating more biogas than needed for their own consumption to package and supply bagged biogas directly to their neighbours. The household which owned the digester were called "Suppliers" and the neighbours whom the biogas was distributed to in bags were called the "Consumers". The following cost components were considered.

6.1.1 Scenario 1: Supplier Side

6.1.1.1 Capital Expenditure Costs

Table 6-1 itemises to all investment costs related to becoming a portable biogas supplier using a peer-to-peer distribution model. This includes installation of surplus devices, piping materials, installation of compression system, and training. The specific costs under this component that were identified from the field are based on costs encountered during this trial. Further work is required in carrying out detailed sensitivity studies of the effects of different cost parameters on viability. It is assumed that these initial investment costs will be incurred by the supplier and expected to be paid back (pay as you go) from the monthly revenue.

S/N	*Item description*	*Cost in Tsh*
1	*Installation of surplus device*	*50,000*
2	*Bag compression system*	*180,000*
3	*Buying bags*	*161,000*
4	*Gas pipe (8m long)*	*25,000*
5	*Clamps*	*6,000*
	Total	*422,000*

Table 6-1 Capital expenditure costs associated with supplying portable bags through a peer-to-peer model

6.1.1.2 Operation and Maintenance Costs

These include recurrent (regular, ongoing) expenditure on labour, materials and minor maintenance to keep the system operating. The real cost that was identified under this component was an average of TSH 500 per month to replace fittings that may wear out. No personnel costs were identified since both supplier and consumer are neighbours and they perform all operations themselves.

6.1.1.3 Capital Maintenance Costs

Expenditure on assets renewal, replacement and rehabilitation covers the work that goes beyond routine maintenance to repair and replace equipment, in order to keep systems running. The costs may be estimated based upon serviceability and risk criteria related to service degradation and failure. The real costs that were identified from the field are summarised in Table 6-2 below.

S/N	*Item description*	*Cost in Tsh*
1	*Buying two bags after 12 months*	*161,000*
2	*Buying new stove after 24 months*	*50,000*
3	*Repair bags compression system after 12 months*	*5,000*
	Total	*216,000*

Table 6-2 Capital maintenance costs for supplying portable biogas in a peer-to-peer model

6.1.1.4 Revenue

The biogas suppliers obtained revenue from selling the bagged biogas at Tsh 3000 per bag.

6.1.1.5 Analysis and discussions:

The above costs components were organised and analysed using an Excel document to forecast and generate trends over a period of 36 months. Annual inflation rate data were considered especially for Capital Maintenance costs in order to account for increased prices of materials in the future.

Our calculations suggest that the supplier will be able to recoup / pay back the investment after 13 months. The forecasting suggested that in the 12th month the supplier will incur capital maintenance costs to replace parts of the system. This will reduce the savings significantly but gain more benefit as time goes by.

6.1.2 Scenario 2: Consumer Side

6.1.2.1 Capital Expenditure Costs

It is expected that the consumer will buy the stove as part of their initial expenditure. This will encourage the consumer to value this asset and take responsibility to care for the stove. This investment is considered as a cost that needed to be paid back. The real cost of the stove was identified as Tsh 50,000.

6.1.2.2 Operation and Maintenance Costs

Based on the field experience in this model no operational costs were incurred by the consumer since he/she is a neighbour to the supplier.

6.1.2.3 Capital Maintenance Costs

Experience from the field shows that stoves last at least 24 months. During the 24th month the consumer will buy a new stove at Tsh 59,488 based on annual inflation rates.

6.1.2.4 Revenue

Consumers revenue is determined by establishing difference of costs he/she incurred by using other sources apart from bagged biogas. The trend in our analysis suggests that when switching from using other sources of energy and starting to use bagged biogas the consumer will save a significant amount of money.

6.2 Cost-Benefit Analysis of Milk-Round Portable Biogas Distribution

The entrepreneurs within a community were identified and engaged to be a biogas supplier, delivering biogas to homes. Their source of biogas was purchasing it from a larger biogas digester that they own. The entrepreneur is expected to meet all investment costs including the stove. So that he/she make the business quicker. Below are the costs that were identified from the field during the trial.

6.2.1 Intermediary/Entrepreneur Side

6.2.1.1 Capital Expenditure Costs

S/N	*Item description*	*Cost in Tsh*
1	*Installation of surplus device*	*50,000*
2	*Bag compression system*	*180,000*
3	*Buying bags*	*161,000*
4	*Gas pipe (8m long)*	*25,000*
5	*Clamps*	*6,000*
6	*Stove*	*50,000*
	Total	*472,000*

Table 6-3 Capital expenditure costs for milk-round distribution of portable biogas

6.2.1.2 Operation and Maintenance Expenditure Costs

S/N	*Item description*	*Cost in Tsh*
1	*Payment to the distributor for 16 bags*	*13,328*
2	*Cost to buy 16 bagged biogas from the supplier at Th1500 @*	*24,000*
	Total	*37,328*

Table 6-4 Operation and maintenance costs for milk-round distribution of portable biogas

6.2.1.3 Capital Maintenance Costs

S/N	*Item description*	*Cost in Tsh*
1	*Buying two bags after 12 months*	*161,000*
2	*Buying new stove after 24 months*	*50,000*
3	*Repair bags compression system after 12 months*	*5,000*
	Total	*216,000*

Table 6-5 Capital maintenance costs for milk-round distribution of portable biogas

6.2.1.4 Revenue

The revenue was obtained by the intermediary/entrepreneur through filling a bag with biogas at a cost of Tsh 1,500 (paid to the digester owner) and selling to the users/consumers at Tsh 3,000 per bag.

6.2.1.5 Results

Based on our forecasting of the costs, no savings/benefit will be attained because of too huge capital and operational costs.

6.3 General Recommendations

Based on our initial cost-benefit analysis in combination with technical prototyping and participant feedback we have drawn the following conclusions:

1. The peer-to-peer model appears more viable than the milk-round distribution of portable biogas. However, peer-to-peer in this trial was relying heavily on the relationship of neighbours who are not necessarily interested in business.

2. Milk-round distribution cannot generate income based on the conditions of this trial. The capital and operational costs were too huge for the distributor to generate benefit.

3. Identifying further ways to reduce the initial investment costs would be of value. Outsourcing means to obtain cheaper and better quality bags and also using more affordable materials for a biogas compression system will contribute to reducing capital costs and hence enable earlier cost recovery and generation of savings (profit).

7 Next steps

7.1 Field trials

The Project Consortium will explore applying for further innovation funding to develop the biogas upgrading technology, as this could have a significant impact on portable biogas becoming a success. A full project proposal including work packages, deliverables, timescales and costs will be prepared for this.

We are continuing to explore potential business model for the packaging and distributing of portable biogas through our Bitesize Energy Exchange (BEE) Project, which commenced in November 2019 and will run for 24 months. This project explores quantifying and then packaging surplus of both biogas and solar alongside assessment of viable business models. A schematic indicating initial ideas for the portable biogas market is illustrated in Figure 8-1.

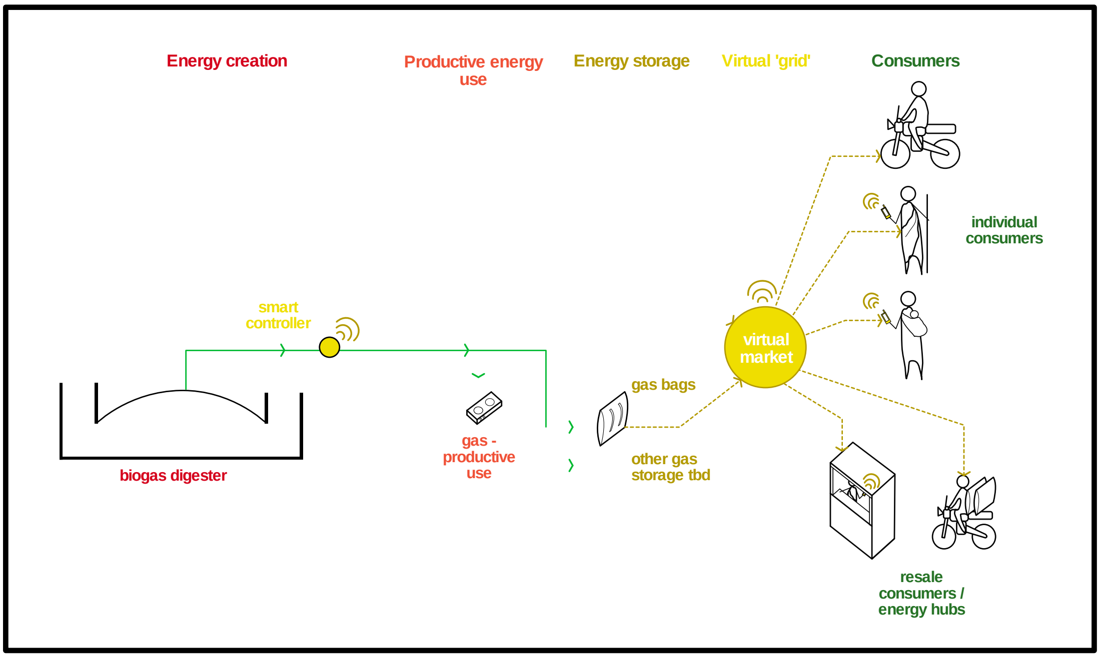

Figure 7-1 Potential business model diagram for the packaging and distribution of portable biogas

CREATIVenergie and ECHO teams are currently designing a larger, and longer-term, field trial of portable biogas in collaboration with Fida's Tanzania office. Funding has already been secured by Fida. The field trial will be conducted in one community where Fida already have community engagement. The project will involve training in biogas digester construction and maintenance, the construction of a biogas digester at a farm, training on filling biogas bags plus using these to supply fuel for cooking with stoves and biogas 'rice' cookers. This field trial will provide an opportunity to further test the business model (price, payment methods, longer-term maintenance, supply and demand). Commencement is in part dependent on the lifting of restrictions to movement in Tanzania currently in place to contain the spread of COVID-19. It is intended to be concluded at the end of 2021.

7.2 Further Innovation

Based upon our research, we suggest that a hybrid approach to distribution of portable biogas may be more viable. Essentially larger higher-pressure vessels would be used to store the biogas and transport it to distribution points, where biogas bags could be refilled for local usage. This would be similar to the way people by fuel from a petrol station. This approach is interesting from several perspectives:

i. Financial - one of the issues highlighted with the size of the bags was the inability to transport more than one at a time, especially by foot, on a bicycle or motorbike. Selling portable biogas from a centralised distribution point would reduce transport costs for the supplier as they would only be travelling to distribution hubs to supply multiple people who travel to them to collect fuel for individual households.
ii. Safety and maintenance - in this model, the supplier maintains pressurised biogas containers, which is easier to regulate. For end-users, transporting biogas at low-pressure (e.g. in biogas bags) is relatively safe compared to in pressurised vessels.
iii. Low capital investment for the end user, as they use biogas bags.
iv. Control over biogas quality - the supplier can clean and upgrade the gas, which is more cost effective for them to do as they will be supplying biogas to more people through this approach than a 'peer-to-peer' model.

Our work to date has highlighted the importance of further innovation around the vessel used to transport the biogas, and this needs to be a specific focus of further work. This includes exploring the material used for the vessel, its size, portability and weight.

Our study has also highlighted the value of upgrading biogas to increase the methane content. Our approach appears valuable, because it is simple and sustainable and does not required specialist materials. However, it needs a full cost benefit analysis to be conducted as well as work on optimising it from a performance point of view.

Any further research exploring the innovation and technical viability of portable biogas, should again be accompanied by qualitative research to determine the best distribution model for portable biogas (including models such as 'existing community hubs' and 'aggregation for productive/commercial use' that were not part of this study). A larger number of participants would be required to draw tangible conclusions on the scale up, financial viability, gender considerations and sustainability of any distribution model. There also needs to be continued efforts to include consumers in such studies to further understand how and why people like using portable biogas and to be able to determine its customer base in the market. Finally, a scale-up of qualitative research is needed to determine the gender, social inclusion and socio-demographic considerations of the portable biogas value chain.

In the context of the COVID-19 pandemic, the CREATIVenergie team saw potential to apply gas compression principles learnt during this project to oxygen concentration. If this proves successful, this could provide an innovative way to generate oxygen in off-grid healthcare facilities including for refugee camps and humanitarian disaster response. In order to explore this potential application, CREATIVenergie submitted a six-month project proposal to Innovate UK's competition *Business-led innovation in response to global disruption*. A response is expected 1st May 2020.

7.3 Dissemination Plan

Dissemination activities conducted during the project include:

i. Presentation at Title, held at the University of Surrey;
ii. Conversations with other MECS project team members and other attendees at the Clean Cooking Conference in Nairobi;
iii. A 'cook off' with participants and other community members in Tanzania (discussed previously)

Future dissemination will include:

i. Publishing results in academic journals (e.g. Energy Research and Social Science);
ii. Writing a blog article for circulation through various biogas networks across East Africa, MECs, LCDN;
iii. Circulation of findings to our partners in other consortium projects.

Figure 7-2 Biogas stakeholders meet project team members during a dissemination event at ECHO East Africa Impact Centre, Tanzania

8 Conclusion

There have been many takeaways as a result of the technical prototyping and qualitative methodology implemented in this project. These takeaways are fully presented in Section 3 Implementation & Findings: Technological Insights and Section 4 Findings: Qualitative Insights. In short, we found that:

- Portable biogas is deemed a desirable fuel comparable with LPG.
    - It needs to be stored in smaller apparatus to be preferable over LPG.
    - Therefore, it is timely to explore alternative options of compressing biogas.
    - The study highlighted and tested the technical feasibility of different ways of compressing the biogas, but we did not evaluate and test the compression methods with end-users. This is an area that needs further research i.e. what compression approach is most viable in different situations.
    - Existing steel canisters are too heavy per unit volume to be able to supply sufficient biogas and be easily portable for peer-to-peer distribution, which was seen as a favourable distribution model. Other suitable materials for the storage vessels are available and costs of manufacturing should be explored. Furthermore, the feasibility of novel storage methods such as an appropriate adaption of ANG for small scale biogas is also worth exploring further, because if this were viable it could have a significant impact on the amount of gas that can be transported in a small vessel at low pressures.

- Supply of biogas is perceived as technically easy to set up and manage but supply is limited due to factors such as size of digester and seasonality. Looking into approaches to secure and enhance the production of biogas during colder weather is important, as this could have a significant bearing on the scalability of portable biogas.

- Bagged biogas cooks food just as well as LPG and is liked especially for its fast cooking.
    - The surplus device developed functions effectively and means supplying biogas to a consumer does not impact the producer's supply of biogas. This is hugely beneficial for portable distributed biogas.
    - Other advantages include easy to light and simple.
    - Challenges include bag leakages, storage, security, availability and not being able to cook all foods (challenges you would also find with other fuels).
    - Issues around the repairability of bags can be dealt with by designing them out of materials which are easier to fix, demonstrated with making a prototype biogas bag out of thick PVC.

    - Challenges around pressurising the gas for usage can be easily solved with an electric pump rather than a mechanical compression system. This was shown to be simple and effective and could be powered by solar energy.
    - Bagged biogas will likely become an additional household fuel which will continue to include biomass fuels such as firewood and charcoal (in line with fuel stacking literature).
    - If, or how, portable biogas can replace other fuels is yet to be determined.

- Peer-to-peer distribution model accounts for traditional community structures and encourages pre-existing relationships which is favourable within communities. Based on our initial work, it appears to be viable from a cost-benefit analysis point of view. More extensive trials are required.
    - Sustainability of model needs to be tested further considering factors such as seasonality, saturation of product, overcoming challenges that may arise, and the use of informal labour such as children in the supply and distribution process.

- Milk round distribution is the more formal distribution route which could have a wider outreach to consumers.
    - This model has additional cost implications on the ultimate retail price of portable biogas potentially putting it out of reach for many consumers.
    - Could work well in urban centres where businesses currently use biogas and have a payroll of staff that could act as distributers using other modes of transport such as motorcycles or vans etc.
    - The initial cost benefit analysis is not favourable for the model explored in this study. Needs further research into economic and financial viability of distribution model.
    - Another hybrid model was proposed that needs to be further researched.

9 Appendices