Energy Research & Social Science 98 (2023) 103007

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Original research article

Towards fair, just and equitable energy ecosystems through smart monitoring of household-scale biogas plants in Kenya

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ARTICLE INFO

Keywords:
SDG7
Uganda
Kenya
Smart energy systems
Biogas
Carbon finance
Pay-as-you-go energy

ABSTRACT

Anaerobic biogas digestors offer a technological solution to facilitate modern, sustainable, and equitable energy access, efficiency, and transition pathways to achieve United Nations Sustainable Development Goal 7 – affordable, reliable, sustainable and modern energy for all. In this paper we create critical evidence, through documenting insights from the Smart Biogas (SB) II project, that contributes to the introduction of (low cost) smart metered biogas energy systems at the household level. Our research objectives were to 1) understand and analyse the lived experience of key SB project stakeholders, and 2) create evidence that can contribute to the widespread adoption of smart biogas meters for household-scale applications.

In early 2022 13 semi-structured qualitative interviews were conducted with key SB II project stakeholders (biogas end-users, system specialists, carbon finance professionals, research partners, and general experts). These semi-structured interviews followed a phenomenological approach focusing on the lived experience of study participants. Our results showed that biogas is particularly suited to live monitoring and the SB system unlocks significant benefits to both the end-user and energy supplier. These benefits are realised through improved user experience, unlocking biogas-as-a-service delivery models and seamlessly integrating remote monitoring capabilities for carbon credit programs, as well as identifying a series of future work pathways across these themes. Ultimately, we show the SB meter enables an accessible and low-cost approach to decentralised energy for households across the globe and a potentially scalable pathway to achieve SDG7.

1. Introduction

Recent years have been full of catastrophe, yet, according to International Panel on Climate Change, the single biggest global scale disaster is still on the horizon [1]. The destabilisation of the global ecosystem, due to the way in which we all extract, use, and consume unsustainable sources of energy, will result in a significant loss of biodiversity, rising sea levels, and violently extreme weather patterns all in the context of an exponentially increasing population. Many sectors are in the process of trying to decarbonise, looking to increase the sustainability of their operations by transitioning to improved or clean or renewable energy production methods, technologies, and services (for example, the UN Environment Program "Greening the Blue" [2]). However, not only are solutions needed that transition existing energy users away from polluting technologies and fuels, but also that react to the increasing global share of population who require energy access to satisfy their basic energy needs in the context of United Nations Sustainable Development Goal 7 (SDG7) [3] - affordable, reliable, sustainable and modern energy for all. Currently, the high infrastructure costs of centralised, national or international energy programs is one of the main barriers precluding citizens in emerging economies from accessing modern, reliable and sustainable energy systems and services [4].

Household-scale anaerobic biogas digestors offer a smaller scale technological solution to facilitate modern, sustainable, and equitable energy access or transition pathways. The process of digestion is, at face value, straightforward. It requires organic matter to be loaded into an airtight container that then creates optimum conditions for anaerobic digestion, whereby the organic matter (animal dung, food waste and black water) is converted to biogas (a mixture of predominantly methane and carbon dioxide, and trace elements such as hydrogen sulphide) and a semi-solid liquid residue called 'digestate' (a nutrient rich fertiliser) [5,6]. The combination of locally, sustainably, and low cost

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https://doi.org/10.1016/j.erss.2023.103007
Received 24 October 2022; Received in revised form 9 February 2023; Accepted 15 February 2023
Available online 22 February 2023

(or free) feedstock and the high-quality products of digestion offer significant and well documented benefits to end-users [7–11]. However, it is of central importance to recognise that these technological solutions exist within the socio-technical framework, as outlined in detail by Robinson et al. [12], which is a balanced ecosystem of technical and social methodologies, i.e. the technology is equally as important as the context specific perceptions of end-users driven by lived experience. These factors are documented in previous work by Hewitt et al. [13] where there are number of socio-cultural, environmental, financial, and technical challenges to the adoption and sustained use of biogas plants. Environmental and technical challenges include, hydrogen sulphide corrosion, maintaining the correct carbon/nitrogen ratio of the feedstock, temperature limitations, water feeding, maintaining an airtight chamber, condensation build up, poorly constructed digestors, low gas pressure, and poor end-user operation and understanding of the technology [5,7,13]. Socio-cultural challenges include, biogas plants being stacked by end-users (due to insufficient gas supply [14]) with other energy technologies based upon convenience, season, taste, type of food, cultural beliefs and social status [14–16]. Financial challenges are based around the ability and willingness to pay for biogas plants and services by end users [13]. Widespread biogas dissemination therefore requires an energy ecosystem of end-user training, legislation/policy, supply chains, seed subsidies and tailored financing. In the global household biogas sector, this ecosystem is facilitated by national biogas programs often setup by Stichting Nederlandse Vrijwilligers (SNV) and Hivos [17–19]. In successful cases the support of governments and NGOs is replaced by free market actors, such as Sistema Biobolsa in Nepal [20], who are then able to operate successfully in the biogas energy subsector.

Narrowing the focus to Kenya, significant progress has been made on the proportion of Kenyan population who have access to electricity, from 6.3 % to 69.7 %, between 2000 and 2019 [21], yet there are significant reliability issues [22]. However, well over 80 % of Kenyans do not have access to modern, sustainable, and clean energy sources for cooking resulting in a significant respiratory disease heath burden [21]. Even with Kenya having the highest potential for biogas at 1.3million households [19], and a history with biogas first being introduced in the 1950s, the uptake of biogas plants remains low with limited policy support [23]. Wassie and Adaramola [24] outline the low priority of biogas as only 17,500 biogas units gave been installed compared to 1,300,000 improved cookstoves and 445,000–470,000 solar home systems between 2005 and 2015. This lack of regulatory support has resulted in a 30 % rate of abandonment for biogas plants [25] and significantly under-exploited market potential [13]. Despite the Finance Act 2021 reinstating VAT exemptions for renewable energy products (solar, wind, clean cooking (including biogas)) biogas is not seen as a policy priority. Additionally, as Clemens et al. [23] state, the VAT exemptions from the Energy Act 2006 "only apply to entire shipping containers of appliances and do not benefit small enterprises. Moreover, the process to obtain duty free status is unclear to entrepreneurs" (p. 25). Little progress on energy policy in Kenya since the Energy Act 2006 and a weak subsidy system (unlike Nepal which has driven the adoption of 300,000 biogas digestors [26,27]) has resulted in limited private sector involvement. The construction of biogas units are primarily driven by African Biogas Partnership Program[1] (ABPP), phase 1 2009-2013, phase 2 2014-2018, (proposed phase 3 2019-2023) not the policy and regulatory environment. SNV notes in their phase 2 project evaluation [28] that, despite structures having been implemented by the ABPP, there is much effort still required to create a fully functioning and independent biogas market including market diversification, setting up an independent quality control regulatory system and clarifying the role of government in taking ownership of quality standards, quality control and research and development.

In this paper we look to explore how the smart metering of biogas units can mitigate many of the challenges commonly associated with biogas failure and abandonment as identified in previous work by Jewitt et al. [13]. We look to use data to enhance diagnostic and servicing tools, explore the potential of the "biogas-as-a-service" delivery model, and better understand the integration of carbon payment mechanisms as a potential pathway to fair, just and equitable energy systems and services. This is in line with central pillars of the Smart Biogas II project (outlined in Section 2.1). Our central aim is to create critical evidence through documenting the core insights generated by the Smart Biogas II project which builds the case for household-scale (low cost) smart metered biogas systems as a viable decentralised alternative technology for the generation and productive use of energy products and services. Our research objectives (RO) are to:

(1) understand and analyse the lived experience of key Smart Biogas (SB) project stakeholders in Kenya.
(2) create evidence that can contribute to the widespread adoption of smart biogas meters for household-scale applications.

This paper contributes the fundamental research on smart biogas systems that can be used to strengthen discourse and promote smart biogas systems as one pathway to achieving SDG7. Our novelty in this paper is three-fold. First, a focus on household-scale smart monitoring of biogas digestors not seen before in the state-of-the-art academic literature. Second, we highlight new areas of attention; for example, the significant impact of methane venting in household-scale systems. Third, we look to connect the biogas end-user with the wider project and global implementation environment to create an energy ecosystem approach to modern, sustainable, and reliable energy systems. Ultimately, we set out to show this approach to decentralised energy systems has the power to address the multidimensional issues associated with processing waste, producing energy, and generating income across resource limited and highly contextualised settings.

2. Methods

In this methods section, first, we introduce the smart biogas system from InnovateUK's "Smart Biogas II - Increasing Wealth from Waste" project (InnovateUK Grant Number 105909). Second, we draw insights from 13 qualitative semi-structured interviews (conducted in early 2022) with biogas users in Kenya and key decision makers from the wider Smart Biogas II project. Third, we triangulate this data with previous work by the authors and secondary data identified through literature reviews the on the relevant sub-sector focus areas.

2.1. The Smart Biogas II project

InnovateUK's "Smart Biogas II - Increasing Wealth from Waste" project is centred around a patent pending innovation, called Smart Biogas (SB), that unlocks three key pillars: 1) remote and automatic fault diagnostics 2) enabling Pay-as-you-go (PAYG) and 3) enabling smart carbon market integration. These pillars are designed to improve end-user experience and ensure the widespread sustained use of biogas plants. This project builds on the insights generated by the first round of funding by InnovateUK through the "Smart Biogas Network" project (Grant Number 132479). By taking a design philosophy of achieving 90+ % accuracy for 20 % cost, the technology is accessible for markets in the global south and significantly undercuts its competitors. The pilot included our data collection was delivered by the Kenya Biogas Programme (KBP) (a delivery partner for the ABPP in East Africa) in partnership with technology supplier Inclusive Energy where SB meters are installed on typically small farms selected by randomised sampling. Additionally, there are other pilots in Tanzania, Uganda, India and the Philippines which are not considered in this paper; however, some

[1] The ABPP aimed to facilitate the construction of 100,000 biogas digestors by 2019 [17] in Burkina Faso, Ethiopia, Tanzania, Kenya and Uganda.

interview participants work across multiple implementation contexts, and this shaped their wider lived experience of SB.

2.1.1. The smart biogas system

The SB system is designed to measure gas pressure and usage in household-scale biogas plants[2] and thus remotely detect faults. The system can be used with any type of biogas plant (bag, floating, or fixed dome digestors), Fig. 1 shows an example. The SB meter consists of static and differential pressure sensors, these sensors send data to the SB web application (typically every hour) via the main Printed Circuit Board (PCB) which is powered by a solar panel. The data is sampled by each sensor every 5 milliseconds and an average result for each minute is stored in the cashed memory. The device itself can cache data for up to one day, with an additional gas consumption counter on the PCB for situations where data connection is lost for more than a day ensuring the end-user can be billed, or carbon credits accrued accurately.

The SB web application captures the remote monitored data and when plotted (Figs. 2 and 3) shows a variety of insights that are linked to the hourly, daily and lifetime use of the biogas plant as well as enabling hardware failures, both in the biogas plants and SB meter itself, to be captured at the individual unit level before cascading across the local or global project levels. As two examples, Fig. 2 shows a perfectly operating plant that correctly sized for the usage pattern, whist Fig. 3 shows an underused biogas plant (either through oversizing or underuse) which is venting biogas (as shown by the horizontal pressure line on the graph). A leaking system will have a flow rate that does not return to zero after consumption events, however, the type of leakage will have to be identified by technicians in person. Additionally, the end-user can access this information through the SB home app which provides a simple summary generated by machine learning algorithms.

As the SB meter data was collected through the private sector partner, we remained compliant with GDPR (through the UK's Data Protection Act) to protect study participants and all participants in this pilot gave their consent to partners of the project storing and using their anonymised data for further research purposes.

2.2. Evidencing lived experience

The resurgence of COVID-19 in Kenya in early 2022 resulted in a significant change in data collection strategy as visits to east Africa by the UK research team were no longer possible. This meant that we had to pivot in our data collection strategy in order to ensure that the voice of the end-users voice was captured within this study, as the authors believe this is a vital element of understanding energy ecosystems. Our approach was as follows; first, through Energy4Impact's (E4i) [29] Kenyan office, a kenayan researcher was given extensive training on qualitative data collection. This included training on outsider status, conscious and unconscious research bias, positionality, as well as how to conduct participant led semi-structured interviews. The E4i researcher conducted 7 in person semi-structured interviews in March 2022 with strategically chosen (by KBP) biogas end-users to give a range of experiences with both their existing biogas system and the integration of the SB systems. Second, the lead author conducted 6 online semi-structured interviews in March 2022 with all key project decision makers in the SB project (based in the UK, Uganda, and Kenya). This included technical biogas system experts, carbon finance professionals, and research partners. Where it was not possible to generate primary knowledge our data collection was supported by secondary data gathered through a literature review of the current understanding of integrating smart systems with biogas plants, Pay-as-you-go or Biogas as a Service models, and intersection between SB and the carbon credit sectors.

[2] Up to 2.5 m^3/h flow rates and 10 kPa maximum static pressure.

2.2.1. Interview design

Using a broadly phenomenological approach [30] focused on the lived experience of our key stakeholders [31] we looked to contextualise the SB meter remote-captured data on the adoption and sustained use of household-scale biogas units from two perspectives; the end-user (conducted by E4i) and the SB key decision makers (conducted by the lead author). These two perspectives required different semi-structured interview guides due to the different expertise of these two groups. However, in both cases it was critical that content was primarily led by the participants (based on what they felt was most important) and directed by the interviewers within the core themes of the interview guides. Additionally, time was left at the end of the interviews for participants to raise any additional thoughts or concerns that they felt were not covered.

The semi-structured interview guide for the biogas end-users was designed to capture understand the socio-cultural, environmental, and financial factors which influenced key decisions associated with adoption and sustained use of biogas plants. We opened the conversations with an open question such as, “tell us about your experiences with your biogas plant?”, in order to set the participant at ease and establish the participant led nature of the discussions. This lead into deeper discussions, shaped by the themes in Hewitt et al. [13], around construction and instillation quality, feeding process, operation and maintained, training provision and knowledge erosion in order to set up the question “how has the smart meter improved this experience?”. Moreover, we asked participants about financial drivers of biogas adoption and sustained use as well as the entrepreneurship opportunities for the excess biogas that participants did not use. Our final theme was around aspirational energy futures in order to understand the future energy use priorities.

The key decision makers semi-structured interview guide also initiated the conversation with an open ended question such as, “what does success in this project mean to you?”. This question was designed to build a trusting, equitable and open environment for the interview. We then focused on three topic areas which had a number of prompt questions. The topics were improved end user experience, developing the “biogas-as-a-service” model and the integration of carbon market mechanisms. The prompts included questions around, project partner experiences, methods to mitigate use barriers, accountability, scale, operational limitations, fair, just and equitable energy systems, and circular economy.

2.2.2. Data transcription, translation and analysis

The interviews in Kenya were conducted by Energy for Impact's (E4i) reseacher in Swahili and then any areas of misunderstanding were clarified between the lead author and interviewer. The interviews conducted by the lead author were in English and transcribed, cleaned, and checked by the other authors. Once the transcripts were collected, all were coded using the same analysis process through Nvivo12. We followed a broadly deductive thematic analysis following the six-step method [30], using the three key project pillars (using data to enhance diagnostic and servicing tools, exploring the potential of the “biogas-as-a-service” delivery model, and integrating carbon payment mechanisms) of the project as the top-level nodes of the coding framework. The coding framework, and sub-nodes, then evolved based on the responses of the participants, reflecting the lived experience of participants and not the wishes of the researchers for pre-determined outputs. This resulted in a matrix of both broad and specific themes with supporting quotes as presented in the findings section. The quotes with numerical tags (1–7) are attributed to biogas end users whilst letter tags (A-F) are attributed to key decision makers.

2.2.3. Limitations

As with all research methods there are a range of generic semi-structured interview limitations that can influence the success and validity of interview data [30], in this section we look to engage with the

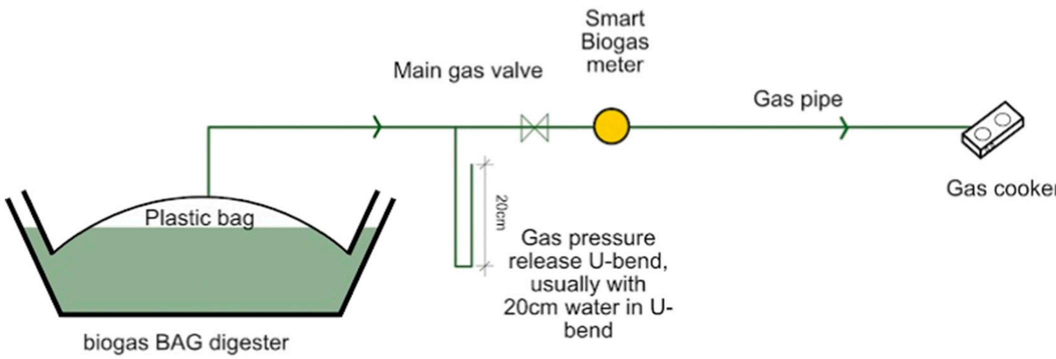

Fig. 1. Type 1 - Bag digester.

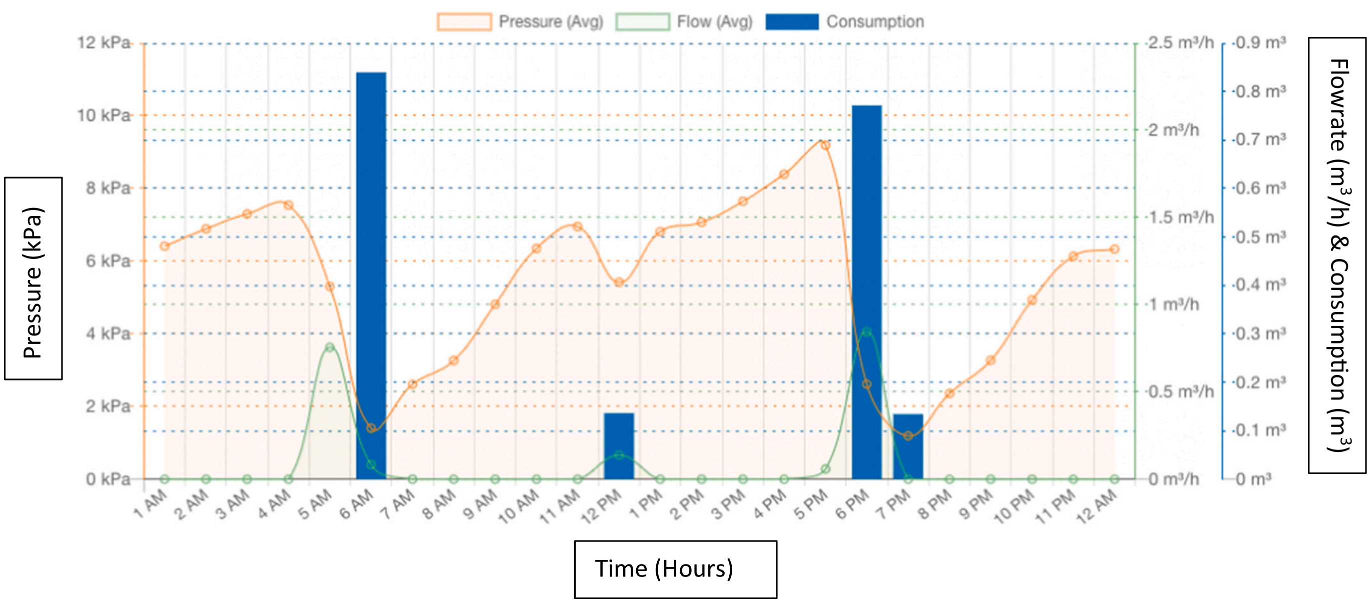

Fig. 2. Plotted SB web app data (perfect operation).

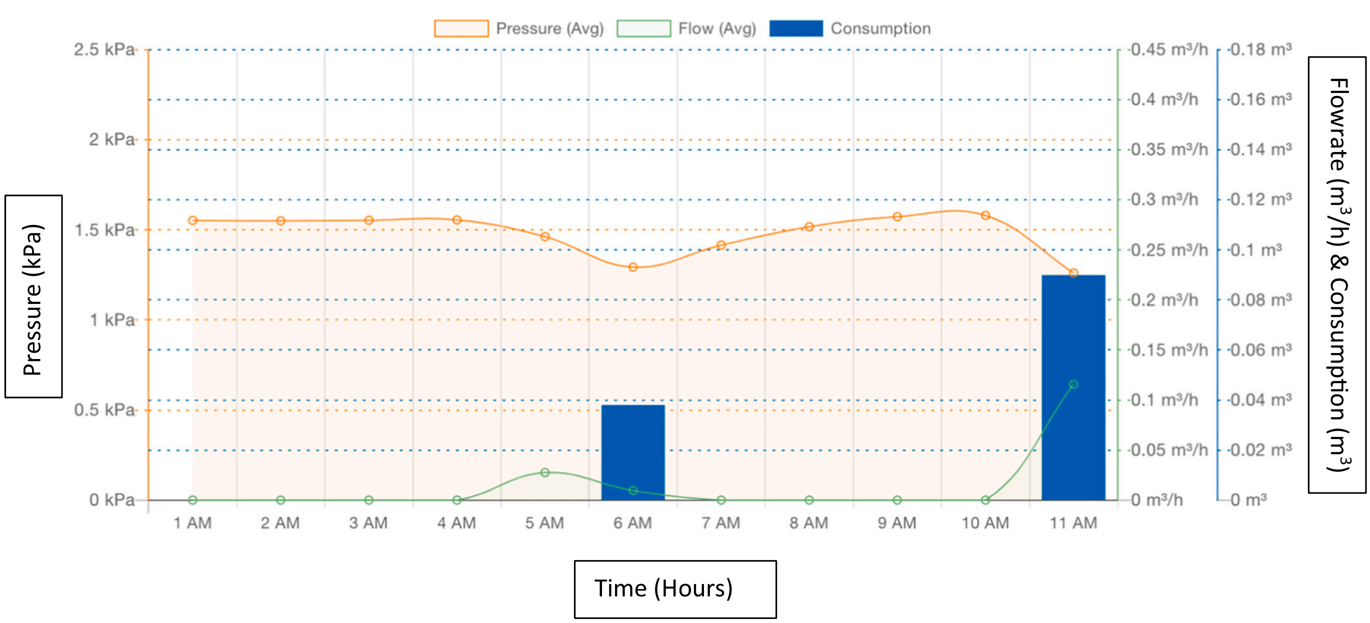

Fig. 3. Plotted SB web data app (venting & under-use).

limitations that directly affect the quality of data in this study.

First, central to any human centred research is the role of pre-existing bias and positionality. This can be realised through leading interview questions or interviewers asking closed questions that can influence the opinions of the participants. In this research, the interviews were conducted by independent researchers (one UK and one Kenyan National both of which have extensive experience in the sector) who had not been involved in the conceptualisation or implementation of the Smart Biogas II project, resulting in an additional layer of openness and objectivity. Additionally, there were significant benefits to having a Kenyan national conduct end-users interviews as the participants felt more at ease with sharing personal information, mitigating the issues associated with outsider status [31,32], as well as the interviewer being more flexible with last minute schedule changes.

Second, due to the time and COVID constrains, biogas end-users were selected based on the recommendation of KBP. Selection criteria included: project site accessibility, end-user availability, inclusion in the smart biogas program, and a willingness to talk to the researcher. This could lead to preferential selections of participants by KBP, which we looked to mitigate by stressing the importance to KBP of interviewing a range of biogas users with different experiences and only conducting interviews with a selection of randomly picked participants from the full list of potential interviewees. Moreover, due to this pre-existing relationship with participants a member of the KBP team was present at a number of the interviews. Some participants shared that they felt more comfortable with KBP present as there was limited time for an external party to build trusting relationships with end-users. In this case it was communicated to the end-users it was of key importance that this would not affect how the participant shared their experiences and if there was additional information they needed to share contact details were provided.

The third limitation was the limited number of interviews with users of biogas. In Kenya this was limited by KBP and their willingness to provide more participants as other biogas participants were part of other pieces of work and they did not want to confuse participants between studies. We looked to limit the effect of this by supplementing primary insights from the wider biogas literature and ensuring that participants could provide a diverse range of biogas experiences.

Fourth, conducting semi-structured interviews online has a number of benefits, for example, there is more flexibility in scheduling, as schedules can be designed around participant availability rather than field visits imposed by researchers, and online methods transcend the geographical limitations of tradition research methods. However, there are limitations around data security, ownership, protection, and transparency when conducting interviews online [33]. In this study we provided participants with an extensive consent form and information sheet that detailed their rights in the research processes, how their data would be used and stored, that they were free to withdraw their consent at any points and that any data they did provide would remain anonymous. We looked to "ensure participants are empowered in their own representations, and given agency in their interactions with researchers" (p. 677) [33] in order to ensure the quality of data. This included, if required, asking for clarifications from participants and providing detailed information on next steps in terms of how this research would be used to generate more effective smart biogas project work.

Lastly, qualitative interviews when translated from their original language can lose meaning. We mitigated this issue by working closely with the E4i consultant who was fluent in each language and could clarify where there were misunderstandings in the transcript.

3. Findings – evidencing lived experience

In this section we present the key themes as determined by our data collection which evidenced the lived experience of Kenyan biogas end-users and key project decision makers across the UK, Uganda and Kenya. We look to engage with the question, "how can the end-users see the benefit of smart biogas systems?", whilst exploring three areas with the potential to accelerate energy transitions and provide pathways to fair, just and equitable energy systems and services. These include using data to enhance diagnostic and servicing tools for improved user experience, reducing end-user barriers to market entry by exploring the "biogas-as-a-service" delivery model, and the integration of carbon credit programs – in line with the key pillars of the SB project. We also directly address the underlying issues associated with biogas plant failure and abandonment [13].

3.1. Using data to enhance diagnostic & servicing tools to improved user experience

In recent years, the rise of smart and remote metered technologies across the globe has enabled many industries and their sub-sectors to develop new systems and services that enable end-users to directly choose, assess, and control their own user experience journey [34,35]. The SB project, through its SB meter, has enabled low and middle-income farmers in Kenya to leverage this remote monitoring method at a fraction of the cost of other commercially available systems. It is well documented that household-scale biogas units have the potential to meet the energy needs of 'disconnected', typically rural, communities across sub-Saharan Africa [8,36]. However, can the remote capture of biogas plant data, designed around our three key pillars, complete this promise to improve biogas user experience?

As part of the previous "Smart Biogas Network" grant, researchers established current user experience with non-metered biogas systems in Northern Tanzania. Whilst there are socio-cultural variations between Kenya, and Tanzania, the broader energy landscape is similar as it is coordinated under ABPP by SNV and Hivos. This was further reinforced by our participants in Kenya facing many similar issues and habits with their biogas plants. Hewitt et al. [13] present this preliminary round of data collection that generated fundamental insights into the user perceptions of biogas as a cooking fuel (and a number of limitations such as the inability to predict when the gas might run out), the causes of poor functionality and failure of biogas plants[3], and user-identified solutions to biogas plant failures. Whilst this understanding of user-perception builds on existing literature that identifies the barriers to the adoption sustained use of biogas plants [5,24,37,38], and takes a step further by enabling the generation of user-identified solutions to these problems, there is still a significant research gap in solving these end-user issues. Thus, by undertaking this initial survey of end-user perception, before the use of SB meters, we look to connect the theory to practice research gap.

3.1.1. Establishing end-user experience

Why do our participants cook on biogas? In Kenya, the participants of our study chose to invest in biogas through formal/informal loans and savings mechanisms either directly with their existing capital or through payment by produce (they would pay down their loan by giving milk or other products to a financial cooperative). This meant that, contrary to the study in Tanzania, our participants did not find the costs of the system a barrier to market entry. But they did stress that for others less fortunate than them, this would be the singular most important barrier, apart from a lack of animals for feedstock.

"*Money or [maybe if] others don't have cows*"

(Participant 2)

The primary drivers stated by the biogas end-users for sustainably using their biogas plants were, convenience, cost savings, the bio slurry or digestate, and safety. The convenience of; being able to cook on

[3] Divided into four themes – Construction and Instillation Quality, Sub-Optimal Feeding Processes, Operation and Maintenance, Training Provision and Knowledge Erosion.

multiple hobs concurrently, no smoke and thus no cleaning of pans resulting in a cleaner cooking environment and no cough after cooking, the reduction (and in some cases abolishment) of firewood collection, and the faster cooking time. However, all participants mentioned stacking cooking technologies [14–16] depending on the availability of biogas (due to lack of feeding), type of food cooked,[4] and even not cooking if there is no gas and it is raining outside so there is no dry firewood.

> "*Other times there would be no firewood so my father would say that he won't buy firewood so we would have to chop up some trees [sometimes] I would even sacrifice and burn my shoes so that the fire could cook up the food to avoid being beaten by my parents. So now this biogas has really come through for me.*"
>
> (Participant 6)

The sustained use of the biogas plants was also driven by both overt and covert cost savings. Overt cost savings such as not buying LGP, firewood, and fertiliser, could be seen as the primary motivator as all participants stressed importance of this. However, whilst covert cost savings, such as time saved collecting firewood, were not directly considered, the participants were all aware that 'time saved' was a significant benefit. Next, the importance of the bio-slurry or digestate produced by the anaerobic process was dependant on the participants preferences. Whilst some participants saw the biogas as the significant benefit, "It is very good because it is clean, it does not have smoke, you cook quickly, cooking pots are clean" (Participant 3), others saw the bio-slurry as a primary driver of use, "The maize that grows from there is very big, coming from that waste (digestate)" (Participant 7). This reinforces the multi-dimensional impacts of biogas digestors across the lives of the participants.

The final driver for sustained use was safety. Many participants believed that the biogas was significantly safer that the LPG cylinders.

> "*Even if you open and leave the [biogas] gas valve on the burner and start a fire, it cannot explode. Even when you leave children by themselves you have no need to be worried […] biogas, it cannot explode.*"
>
> (Participant 1)

> "*You know even when the gas is in excess, and it escapes it does not cause any damage but for a normal gas cylinder the damage can be fatal.*"
>
> (Participant 2)

However, as illustrated by Participant 1, there may be some misconceptions about the practical reality of this perception of safety. Unfortunately, this was also propagated by technicians, possibly driven by practitioner knowledge rather than scientific fact, as explained by Participant A.

> "*I went to a very small room, with a bed and a little stove, and in one of those rooms that was where you had a very serious leak, a lot of gas. There's someone sleeping in a space that's filling with [a] potentially deadly gas. So, it was this sort of concerning to me that that wasn't an immediate red flag to the technicians.*"
>
> (Participant A)

Despite the participants of our study vigorously advocating for biogas plants, there were a number of drawbacks stated in the interviews. These drawbacks included the ability to both detect and determine leakage of biogas from the stove, pipes and plant, having to regularly mix feedstock, only being able put a certain size of pot on the stove (for bigger pots firewood was still used), water blocking the gas pipes, not knowing how much gas is left and finally, participants worried about overfeeding the unit: "If I over-feed it will develop cracks [and] explode" (Participant 5).

3.1.2. Can the smart biogas meter improve user experience?

As identified through the interviews with key project decision makers, the SB meter has the potential to improve this experience in a number of key areas: more effective post-sales support, quality control/safety, biogas system ease of use, and understanding productive uses of energy.

First, from the supplier's perspective is critical to provide more effective post-sales support (in addition to knowing whether units are operational) in order to close gaps between the users perceptions of the technologies and the actual realities of performance. Currently, when faults are identified by users, they must call the supplier and the supplier will send a technician to diagnose or fix the issue. The SB meter can improve the efficiency of this process as technicians do not have to physically visit the user to fault check. But, this would require retraining of technicians to use this SB system in addition to addressing the common misconceptions (especially around safety) driven by practitioner experience.

Second, the SB unit can improve quality and safety of biogas units as leaks can be identified automatically and users/technicians notified of potential failures through a SB app. The automation of this identification process would mitigate issues of technicians and users being immune to the smell of gas. These systematic improvements can be made over a range of biogas unit types as the SB system can be used in combination with any digestor design, mitigating both specific and general drivers of failure and abandonment [13]. However, some users expressed reservations around the continual monitoring of their units and stated concerns around energy suppliers being able to monitor other household activities. These concerns stem from the lived experience of sub-Saharan Africans through colonial development mechanisms exacerbating hidden power structures [12].

Next, the SB unit can directly address issues around ease of use and the amount of gas left in the digestor. Whilst many of our participants had pressure gauges this only gave a rough estimate of how much gas was left in the digestor and participants would rather not take the chance of running out of gas. Through the SB home app, users can accurately check how much cooking time was left, additionally this could generate an understanding between input materials and quality of gas. Resulting, for example, in minimising water usage that might be needed elsewhere (e.g. agriculture) allowing biogas end-users to use resources more effectively. Additionally, the presentation of this data could mitigate issues of knowledge erosion [13], as stated by Participant C:

> "*there is erosion of that kind of knowledge and information and many of them die along the way, so to sustain the growth of the sector there's need for continuous training*"
>
> (Participant C)

Finally, all the study participants were interested in the productive uses of excess energy as a method of increasing the value of biogas to the end user e.g. by selling gas to a neighbour. However, before this process of generating additional income from the excess biogas can occour, there needs to be a better understanding (and recording) of usage. Then organisations, such as KBP, can provide users with other systems or technologies than can use the excess gas (such as additional machinery and lights).

3.2. Reducing financial barriers to market entry for biogas stakeholders

As outlined by Diouf and Miezan [39], Nevzorova and Kutcherov [16], and Hewitt et al. [13] a major barrier to market entry is the ability of biogas users to finance biogas plants as biogas technologies have a disproportionately large initial investment when compared to the costs of use and maintenance. Whilst there are a number of financial mechanisms available to users, such as micro or community financing models,

[4] Participants could not cook some traditional foods due to the long cooking times and the worry that biogas may run out halfway through the cooking process

these often do not reach all biogas users and can in fact increase costs for the technology providers. The SB meter generates two pathways for reducing this barrier to market entry, first, by enabling a biogas-as-a-service delivery model at the point of use to spread the initial investment over a longer payment period based on the use of the system rather than standard monthly payments. Second, significantly reducing the monitoring costs can enable more complete post-sales support and the integration of carbon credit programs.

3.2.1. "Biogas-as-a-service" with smart biogas meters

Reflecting the hardware approach of other energy access sectors which are reliant on technological solutions (such as Solar PV Home Systems [40,41] and Improved Cookstoves [42]) the household-scale biogas sector has often focused on the development of more effective biogas digestors rather than co-developing energy ecosystems that look to overcome the complex socio-cultural, financial, environmental, and technical factors that act as barriers to the adoption and sustained use of technical solutions. This energy ecosystem approach includes the development of financial delivery models [43] such as energy-as-a-service, which IRENA [44] defines as "an innovative business model whereby a [energy] service provider offers various energy-related services rather than only supplying electricity. Providers can bundle energy advice, asset installation, financing and energy management solutions to offer a suite of services to the end consumers." (p. 6).

Biogas as a service looks to embody the key energy-as-a-service principles to household-scale SB systems in an effort to move past the standard monthly payments of traditional energy services to "power purchase agreements". A power purchase agreement requires smart metered energy systems and allows end-users to pay per desired unit (hour/day/month) which results in optimised consumption. This can significantly reduce the financial barriers to purchasing and operating a biogas digestor [16,38,39]. Whilst organisations such as PayGO [45] are providing Pay-as-you-go services for LPG cooking, there are no services available to household-scale biogas digestor users that use live metering to determine the cost to users. This creates an opportunity for this paper to establish the biogas-as-a-service narrative.

We approach the theme of financial barriers from two perspectives, the biogas user and the energy supplier, in order to better understand the key barriers that need to be overcome for the success of the biogas-as-a-service model.

3.2.1.1. From the perspective of the biogas user. As stated by Participant D the affordability of the biogas plants is the central barrier to adoption from the perspective of the user, "especially in Uganda [which has a similar operating environment to Kenya] […] the biggest problem of adopting biodigesters is affordability", however they go on to suggest the viability of the pay as you go model, "But we see the biggest opportunity for the populace is in the pay as you go model. So, if the SB meters can be integrated then it would allow more people to improve their livelihoods through that" (Participant D). The issue of affordability is multidimensional and reaches beyond the high cost of the biogas technology and seasonal variation in income.

The first dimension is the investment priorities for end-users. Biogas (and also other sustainable energy technologies) are seen as luxury expenses rather than basic services as other energy alternatives are seen to be cheaper in the short term, such as firewood or charcoal.

> "*So probably if you're looking at the main things around food, health, education and housing, it's probably going to come after luxury. So biogas is pretty low on the list and only features as a priority to areas where their forests have shrunk, where you do not have available fossil fuel*"
>
> (Participant C)

Participants shared their additional concerns that the SB unit may further increase the cost of the biogas plant and push the technology down the investment ladder, "but now you're adding another cost to it so that we really have to work hard to convince the market, the users, this is indeed going to be of benefit to them" (Participant C).

Second, attitude (and access) to finance. Financial institutions are seen to be unjustifiably expensive, "right now the average cost in microfinance institutions that would do these kinds of loans for smallholder farmers are charging anywhere up to 36% interest" (Participant D). Moreover, to access these loans formal financing institutions require collateral which often includes the user's home.

> "*They're [biogas users] very risk averse to putting the very little security they have, which is probably a small plot of land of an acre. That's everything he owns*"
>
> (Participant D)

> "*Possibly now introducing collateral is what actually makes people be scared [to get a loan] in the 1st place*"
>
> (Participant C)

Third, the process of land fragmentation has led to further reduced collateral that is not deemed significant enough to secure the loan.

> "*We have a family with the head of the house that that has two or three acres, but then he splits it up among his five children, and each one has a smaller and smaller piece. And that's really all they have as collateral*"
>
> (Participant D)

3.2.1.2. From the perspective of the energy supplier/financial institution. Currently, both the energy technology supplier and the financial institution (who may be required to finance the biogas unit) may only observe the functionality of the biogas systems through physical site visits. The SB meter can provide live in-built monitoring systems that can be access remotely. This has the obvious benefit of streamlining the communication process so that time is not wasted by either the user or the energy supplier (or financial institution) in physically checking systems across large areas. However, there is still a significant barrier around what happens when biogas users chose to not repay their loan and the associated payment control mechanisms.

> "*But in the case where a household say for instance, failed to facilitate the payment of the system […] what recourse does this technology provider have? Uh, in the past people have thought of shutting off, but then shutting off also comes with another moral obligation of venting […] so that is part of the unresolved offering around Pay go.*"
>
> (Participant C)

Especially in situations where the asset cannot be recovered as it is built into the biogas users property, "but for fixed systems that cannot be moved or recovered should there be default on the part of the user, there still remains a gap there for the kit" (Participant C). Additionally, by shutting off the gas feed the energy supplier is restricting the users access to a sustainable energy source and may force the user to backside to firewood or charcoal fuelled technologies, directly impacting the local natural environment.

The generation of monitoring data can also accurately determine cultural cooking practices resulting in payment models that align with cultural cooking practices. This means that payment schedules are based on realistic estimates of biogas use that integrate cooking behaviours such as seasonal variations in cooking times, location, food types and fuel types in order to balance commercial interests and what is best for the customers or biogas users. This relationship between supplier and users can be collaborative as suggested by Participant D, "there's a lot a lot to be gained by improved user behaviour. We can understand what they're using, what they're gaining and what they're wasting".

3.2.2. Reducing carbon credit monitoring costs

At COP26 [46] carbon markets were a central topic of discussion as this policy mechanism has the potential to enable the de-carbonisation of major industries at the lowest cost point either through carbon taxation or carbon emissions trading systems (ETS) [47]. Voluntary and mandatory carbon markets, as a part of ETS, are particularly relevant to decentralised household-scale smart biogas systems as biogas projects can provide a significant monetary value in terms of emission reduction impacts – around 465USD/tonne of reduced CO_2 emissions compared to wind at 21USD and improved cookstoves at 267USD [48]. However, when ETS cross international boundaries, where the producer of emissions (often based in a high-income country setting) offsets their carbon in a different country (often low-income) this can exacerbate historical inequalities driven by exploitative narratives [49] to create carbon colonialism [50]. As participant B stated:

"*If you were really rich in the Middle Ages and you worried about your soul going to purgatory. You employed a sin eater who would take on your guilt for your sins, [this] smacks of the same thing, just the rich just not wanting to change their behaviour, but saying actually we'll give a few quid to someone to take this up*"

(Participant B)

"*But in and of itself as carbon offsets market itself is also usually quite a debatable topic, whether it's really helping from a moral point of view.*"

(Participant C)

Thapa et al. [51] state whilst carbon credit schemes have seen widespread attention, household-scale biogas units have remained largely unexplored especially when using carbon process to reduce financial barriers to adoption for end-users. Current focus seems to be on other technologies, such as solar PV electrical generation [52] and transition to improved cookstoves [53,54], rather than household-scale biogas units. Smart biogas systems when, combined with a new generation of carbon offset systems, could provide significant and scalable pathways fair, just and equitable energy systems and services [55]. However, the costs associated with carbon projects and the time to recover these costs from carbon certificate sales is considerable. At a given certificate price, the threshold size (in annual tonnes of CO2 equivalent abated) is set by the upfront and running costs, which are largely comprised of Registration, Monitoring, Reporting and Validation. Thus, the lower costs, the lower the critical threshold size (i.e. number of biodigesters) a carbon project needs to break even. As Participant D stated, it is critical to reduce the cost of carbon monitoring so to build a connection between the person generating the carbon offsets and the person financially benefitting in a benefits sharing model:

"*I mean we spend more than 50,000 euros every year just to validate this at a national scale [and] who would bear that expense to get to that point of critical mass of [SB] units deployed for it to be valid*"

(Participant D)

"*we would have to be able to credit the farmer because ultimately the farmer is the owner of those carbon rights. We would love to be able to give that credit back […] But yeah, there's overhead costs that sometimes take more than what you get back or very close.*"

(Participant D)

An accurate carbon pricing systems could result in household-scale decentralised biogas systems being a route to fair, just and equitable energy access across the globe when deployed at large scale. This is a significant an opportunity to "promote innovations and deployment of decentralised power systems" (p. 18) [44] that are critical to the completion of SDG7. However, we identified a number of barriers to the transformation of the carbon abatement system. First, as showed by our interviews the entire carbon abatement system is not understood by end-users as they are deemed a link in the value chain rather than the central element. Second, given the continuous need for technician training and re-training on a mostly consistent energy technology, it raises the question of how adaptable biogas technicians would be to the integration of smart systems and thus a significant role change (given the lack of physical monitoring). Third, by increasing the quality of monitoring data a better understanding of passive venting may negatively impact the financing carbon model. Venting of a single unit has previously not been deemed significant, however when identifying 10s, 100s or 1000s of units venting methane (with 28.5 times the global warming effect of CO_2 [56]) this could pose a significant environmental risk and undermine the benefits of the carbon offset.

4. Future work

As we have presented throughout this paper, SB systems are critical in the scaling of the biogas sector to complete SDG7. However, there are a number of areas of future work that are required for this transformation. First, the SB home end-user app must be developed to show real time information on the use and health of the biogas plant to the end-user. This also helps overcome the failures that energy suppliers often associated with user error, as the collected data is a universal truth.

"*And we've had quite a few instances within that sample size of 60, where we've now gone out into the field to install and then when we reach there in person, they said well the digestor is not working so well, but you just communicated over phone that you have no problems*"

(Participant D)

Second, further technician support and training is needed to upskill technicians for working with the SB system. The increase of information available to both the user and technician will allow further productive use pathways to be identified and acted upon. However, as stated by Participant B, this process must not lose sight of the lived experience of the biogas users themselves, "I think that the qualitative lived experience of biogas users remains absolutely vital to this, there's a real lack of qualitative capacity in Sub-Saharan Africa both in the academic and private sectors" (Participant B). The generation of better data means that more attention is required mining the monitoring data to establish trends, "I think there's a whole piece of work arounds understanding the data [from the SB unit]: usage vs. size, venting vs. economic viability both with biogas and bio-slurry)" (Participant A).

Third, participants shared concerns around the longevity of the SB unit as illustrated by participant C, "you're looking at a biogas system that probably is likely to last 25 years. I don't know whether the kits would last that long". Further work will include increasing the SB meters robustness and durability. Fourth, future work is needed in mitigating issues around loan defaults as well as understanding which organisations are responsible for pre-financing the biogas-as-a-service model:

"*But it's still now requires one entity to pre-finance that until it's paid off. So it's still adding cost somewhere and this has to be one entity that has to be able to provide credit for all the units to be installed and for that cost to be recovered overtime*"

(Participant D)

Finally, there is still work to translate theoretical the conceptualisation of a shared benefit carbon abatement program into reality. A better understanding of venting and the quality of biogas produced is critical to the sustainability of funding.

5. Conclusion

In this paper we set out to document the core insights generated by the Smart Biogas II project which could solidify smart metered biogas systems as a viable alternative technology for the generation and productive use of energy at the household level. In line with our first research objective, to understand and analyse the lived experience of key SB project stakeholders, we conducted 13 semi-structured interviews with biogas users, system specialists, carbon finance professionals, research partners, and general experts across the UK, Uganda and Kenya. This resulted in the primary drivers of adoption and use stated by the biogas end-users being convenience, cost savings, the bio slurry or digestate, and safety. The SB meter, as a response to end-user experience, has the potential to improve this experience in a number of key areas through, more effective post-sales support, quality control/safety, biogas system ease of use, and understanding productive uses of energy. We found that biogas is particularly suited to live monitoring and SB systems add significant value to biogas projects resulting in unlocking benefits to both the end-user and energy producer.

"*The [SB] unit puts the power in the hands of the user, so the user can tell my system is full by just looking at the app and even telling them their system is leaking. These kinds of things are very powerful, the power in the hand of the user.*"

(Participant C)

"*So they're [the biogas suppliers] really looking forward to having this kind of system in all their digesters [...] her comments was, 'this is the technology of the future for us'.*"

(Participant D)

As per research objective two, to create critical evidence that can contribute to the widespread adoption of smart biogas meters for household-scale applications, we then looked to understand the wider implication of utilising the SB technology. By taking a primarily financial lens we explored the implications of the biogas-as-a-service delivery model from two perspectives. First, the investment priorities, attitude (and access) to finance, and the impact of land fragmentation on end-users. Second, from technology supplier perspective where the introduction of in-built monitoring systems significantly reduces costs for the suppliers, with the added benefit of being able to determine cultural cooking practices and design payment control mechanisms that benefit users. We also set the scene for the introduction of a smart metered carbon abatement system and outlined a series of barriers, such as how adaptable biogas technicians would be to the integration of smart systems and how to build a connection between the person generating and benefitting from the the carbon offsets.

Lastly, we identified a number of critical pathways for future work, these included a better understanding smart meter data, further technician support and training, increasing the SB meters robustness and durability, mitigating issues around loan defaults, better understanding of venting, and monitoring the quality of biogas produced. However, it is critical throughout all these areas of future work the SB system must not negate the importance of integrating the lived experience of biogas users. Ultimately, in this paper we showed the SB meter has the potential to enable an accessible and low-cost approach to decentralised energy for households across the globe and a possible scalable pathway to achieve SDG7.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This research was made possible by InnovateUK's "Smart Biogas II - Increasing Wealth from Waste" (Grant Number 105909). The authors would also like to thank Wayne Dwallow from the Energy 4 Impact team in helping facilitate the data collection process.

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