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Clean fuel switch: Exploring the multiple benefits of biogas

A working paper by the Cambridge Institute for Sustainability Leadership

The University of Cambridge Institute for Sustainability Leadership

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Executive summary

"*Air pollution from household fuel combustion is the most important global environmental health risk today.*" [1]

Forty per cent of the world's population burns wood, charcoal and animal dung ('biomass') for their household's cooking and heating. The resulting smoke pollutes the air, burdening families with disease. Indoor air pollution causes an estimated 2.2–4.2 million premature deaths worldwide each year. In Kenya, acute respiratory infections are responsible for an estimated 14,000 premature deaths per year, many attributed to household air pollution.[1]

In low-income countries, where access to electricity is expensive, unreliable or non-existent, the demand for cooking energy is rising in line with population trends, increasing pressure on already scarce wood resources. Kenya's national forest cover had dwindled to around 8 per cent by 2016.[2] As part of its government's efforts to raise this figure to 10 per cent by 2022, a ban on charcoal production was put in place in 2018. However, more work is required to offer families alternatives to biomass burning, particularly those with least scope to adopt new fuels.

In 2018 the Cambridge Institute for Sustainability Leadership joined forces with the science and healthcare company, AZ, to explore this problem. The resulting project sought to equip a low-income community in western Kenya with a clean, green alternative cooking fuel – biogas – and monitor how the resulting 'fuel shift' was perceived, trialled and ultimately embraced by its households.

Biogas is produced through the natural process of anaerobic digestion of organic waste products such as animal dung, cooking waste and plant material of all kinds. It is an effective off-grid energy solution in low- and middle-income countries lacking access to affordable electricity. Once the correct equipment is installed, the costs of producing biogas are negligible provided households have access to organic feedstock and water. In this sense it may be regarded as 'pro-poor'.

Biogas is an extraordinarily powerful development tool, combining multiple benefits (and hence Sustainable Development Goals) in one package. Produced in the immediate environment of a household, it does not require long (and sometimes exhausting and dangerous) journeys by women and children to collect firewood. It burns cleanly, reducing indoor air pollution. It lessens demand for wood resources, addressing deforestation and climate change. As a by-product it produces a rich fertiliser known as bioslurry for use on gardens and crops. Most of all it provides far greater flexibility to households in terms of 'on/off' functionality, safety (in comparison to open fires) and control over cooking temperature – a combination of which means the time of family members responsible for cooking can be freed up for other, more productive purposes.

Several aspects have hindered the success of biogas initiatives in Kenya and elsewhere. The pilot project described here builds on some key lessons from previous experiences, notably the importance of in-situ technical support offered to both the households and the community scale biogas plants established on the lakeshore, which tested the potential for a self-financing enterprise.

The project site is Dunga Beach on Lake Victoria near Kisumu in Western Kenya, where the community relies heavily on purchased wood and charcoal alongside papyrus collected by hand. The land is rocky without significant tree cover, meaning the provision of energy is a constant chore and expense. Interestingly, a very significant source of organic material is accessible from the lake next to the village: water hyacinth, an invasive weed clogging parts of Lake Victoria and its surrounding river basin, is prolific.

The project selected 50 households in the community to receive an innovative 'flexi' biodigester designed and built by the Kenyan enterprise, Biogas International. Households were selected on the basis of need, vulnerability to air pollution and ability to manage the biodigesters after they had been installed. Alongside the household digesters ($8m^3$ capacity), two larger digesters ($60m^3$ capacity) were installed at a prominent site on the lakeshore to provide a base for technical support and biogas enterprise development. The latter offers a combination of metered gas (piped directly to the customer) and metered cooking services on purpose-built kitchenettes suitable for a principal beach activity, fish frying.

Over the ensuing year a range of important insights were gathered of potential value to biogas initiatives in similar locations worldwide.

1. Households embraced biogas cooking, taking care to maintain equipment; however uptake of cooking services from the community biogas plant was mixed

In the 38 households surveyed before and (several months) after their biodigesters were installed, families reported that their biogas stoves were convenient, smoke free, clean and hygienic, cooking food faster and kept utensils clean. Two thirds of them noted that their health had improved within three months, with less eye pain, fatigue, flu and asthma, and fewer coughs, headaches and back problems (from carrying wood). Independent measurements of indoor air quality in 12 households in the community (eight with biogas and four without) demonstrated that carbon monoxide (CO) emissions were reduced, although particulate matter (eg PM2.5) was little affected, possibly due to the primary source of these emissions being the food itself rather than the fuel.

Uptake of cooking services at the community site was slower. After installation, technical modifications included adaptation of stoves to larger woks used by the commercial fish fryers and metering for individual stoves. Social and commercial hurdles have proved challenging, with protracted negotiations on gas prices leading to an underutilisation of gas capacity. Alternative customers have been attracted, including local restaurants, while the potential for sales of bioslurry (as fertiliser) is being investigated.

2. The health and socio-economic benefits of biogas are clear for households

Households benefited economically from biogas, saving around US$19 (1,980 KSh) per month which would otherwise have been spent on conventional fuels. This represents as much as 10–20 per cent of average income in the community, proportionally more for the poorest elderly, female-headed households. Families use this money on food, household items, schooling costs and for savings groups (SACCOs). The quantity of charcoal used in weekly cooking reduced by 45 per cent, wood by 83 per cent and papyrus by 90 per cent. Interestingly, men, children and grandchildren have become far more involved in cooking. This mostly results from the sheer practicality and ease of use of biogas.

The by-product of anaerobic digestion, bioslurry, is underused. This is not surprising: Dunga is a fishing, not a farming, community with no significant cultivation in evidence (food is bought with the proceeds of fishing and other trades). The scope for using bioslurry is reduced further by Dunga's stony ground – it is a rocky outcrop in the lake. The biogas enterprise on the lakeshore is experimenting with 'vertical gardens' to help families utilise their bioslurry to grow vegetables. It is also exploring the potential to market this valuable fertiliser to farmers outside the Dunga community.

3. Water hyacinth has proved to be a viable feedstock for the community biodigesters

These larger-scale biogas plants have been in continuous operation since March 2019, producing high volumes of biogas from shredded water hyacinth feedstock. Identifying solutions to the clogging of Lake Victoria by water hyacinth, including the port of Kisumu, is a national priority for Kenya due to its economic reliance on fishing, trade and tourism locally. The prospect of biogas production offering a win–win solution to dealing with invasive weeds such as water hyacinth while providing a clean, green source of energy is intriguing. As the hyacinth moves seasonally, when unavailable a combination of invasive weed species and restaurant wastes are now being used successfully as feedstock for biodigestion at the community site.

While households have been invited to collect their own supplies of water hyacinth, and shred them at the community site, to date most are feeding their digesters with cow dung and household organic waste.

4. Either a subsidy or credit model is needed to scale up household biogas deployment, whereas the community biogas enterprise needs further time to define its business model

The majority of households receiving biodigesters committed to pay a notional amount of US$50 (roughly 1/8th of the actual cost) to the installer to foster interest in and ownership of the equipment; those classed as ‘extremely poor or needy’ were exempt from such payments. Now that the benefits of biogas have been demonstrated in the community, many more families have asked for an installation. In lieu of a continuous subsidy being available from a public or private source, a logical alternative is a credit model in which the cost of the digester is covered through a series of regular payments post installation, either to the equipment provider or via a financial intermediary (SACCO, microfinance institution (MFI), bank). In this way the high upfront costs are managed through small contributions over an agreed term.

The community biogas enterprise on the lakeshore has successfully exchanged gas for income from a cooperative of women practising fish frying on the beach. However, this income does not cover the full outgoings of the enterprise, and higher gas prices, increased numbers of customers and alternative revenue streams (eg from bioslurry sales) are all under consideration. The innovative nature of the enterprise and its novelty within the Dunga environment mean that lead times to break even have been longer than expected.

The project reveals a number of gaps in the evidence on biogas development in low-income communities:

- To strengthen the case for biogas deployment at national and international levels, **more robust evidence on indoor air quality** is required in households before and after switching to biogas, complemented by **direct monitoring of key health variables** in households with and without biogas.
- Evidence on the reduction in **biomass consumption, avoided deforestation and carbon mitigation benefits** would further substantiate the case for biogas adoption. In addition, the potential for biogas to **address invasive weed growth** should be investigated as a matter of urgency – like air pollution, this is a major global problem.
- The **financial and social sustainability of biogas enterprises** should be explored to understand the conditions in which they can be successful. Cases in urban and rural areas and public services (eg schools and hospitals), drawing on different feedstocks (eg human and market waste, invasive weeds) would help to identify the support needed to make such enterprises financially and technically viable, and socially acceptable. Further discussions with financial providers and key government departments (Energy and Health) could explore how to scale these installations at household and community level.

1. Impacts of biomass for cooking on health and livelihoods

Cooking with polluting fuels causes huge health problems across the world. In 2010, 40 per cent of the world's population, nearly three billion people, relied on wood, charcoal and animal dung (ie biomass) for household energy and cooking needs. In sub-Saharan Africa around 80 per cent of people cook with biomass over open fires, or indoors over charcoal in badly ventilated buildings or kitchen sheds.[3]

The public health threat is severe. Emitted pollutants including particulate matter, carbon monoxide and other airborne chemicals cause increased risk and occurrence of respiratory infections and illnesses, heart disease, stroke and lung cancer, amongst other illnesses.[1] Worldwide, diseases relating to indoor air pollution in households cause between 2.2 and 4.2 million deaths every year,[4] the tenth highest contributing factor to global levels of premature death.[5] Young children and women suffer more; they are more vulnerable or are exposed for longer periods to the cumulative effects of household smoke.[3]

Indoor pollutants related to cooking[6] include:

- smoke made of fine particulate matter ($PM_{2.5}$) less than 2.5 micrograms per cubic metre
- coarser particulates (PM_{10}) of 10 micrograms per cubic metre
- carbon monoxide (CO)
- airborne endotoxins from bacteria
- other chemicals including polycyclic aromatic hydrocarbons (PAHs), arsenic, aldehydes, nitric oxides, benzene and sulphur dioxide.

In response to this threat, the World Health Organization (WHO)[1] has set air quality guidelines for human health. Most households using biomass for cooking have levels of airborne particulates carried in smoke that greatly exceed these limits.[7] In Kenya for example, acute respiratory infection, often caused by household air pollution, is one of the top five causes of death, with an estimated 14,000 premature deaths each year.[8,9]

The need for fuel for cooking and energy also affects livelihoods. Women, in particular, spend a lot of time collecting and processing wood fuels, which can cause additional health issues such as back problems.[10] In urban and peri-urban areas, where wood and other natural fuels are scarcer, households can spend a significant proportion of their income on wood, charcoal, paraffin or liquefied petroleum gas (LPG).[11]

Forest cover has also greatly reduced. In sub-Saharan Africa, 70–80 per cent of wood consumption is for energy, driving forest degradation and deforestation.[12] Around 90 per cent of rural households in Kenya use firewood for cooking and heating, and the country is the highest consumer of charcoal in East and Southern Africa,[13] with 80 per cent of urban households using it for cooking.[14] Forest cover is very low – currently 7–8 per cent of the total land area according to 2010 and 2016 Food and Agriculture Organization (FAO) data.[15] The government and United Nations Environment Programme (UNEP) 2019 'Greening Kenya' initiative seeks to increase forest cover to 10 per cent by 2022.[16] Impacts of decreasing forest cover include declines in animal and plant species, wider ecosystem deterioration and increased carbon emissions due to loss of biomass and burning of fuel.

2. Dunga Beach Biogas Project design

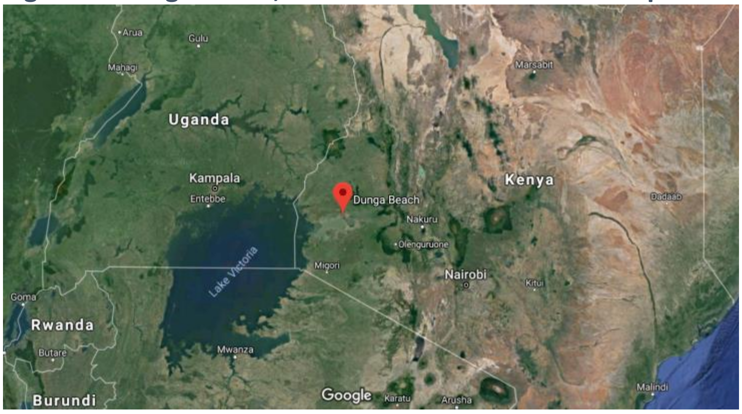
2.1 Approach and project design

The Dunga Beach area of Kenya is experiencing pressures on the environment and livelihood opportunities. Lake Victoria experienced a recent huge decline in local fish stocks due to commercialisation of the fishing industry, overfishing with illegal equipment, water pollution and invasive species (the Nile perch has decimated several fish species and water hyacinth has flourished in conditions of excess nutrients due to water pollution).[17]

Given the need for clean renewable energy to address Kenya's household air pollution, health and environmental situation, this research project investigated the feasibility of biogas technology at local and community levels. It assessed its uptake and impact in four main areas:

1. The introduction and uptake of innovative technologies in the target community.
2. Observed health and socio-economic benefits for households and enterprises piloting a Kenyan-originated clean fuel technology.
3. The ability to use an invasive weed (water hyacinth) from Lake Victoria as feedstock for biogas production, converting an environmental problem (clogging) into a community development opportunity.[18]
4. The potential for scaling up deployment of the technology through financially and socially credible business models to benefit the many lakeside households and fishing communities.

Figure 1: Dunga Beach, situated in the north-eastern part of Lake Victoria in Kenya



2.2 Project overview

The first initiative installed 50 household-scale biodigesters (each 8m^3 capacity), including an earlier pilot of four households. The second initiative built two large community-level biodigesters (total 60m^3 capacity) producing gas for commercial use by local fish fryers and other small businesses on the lake shore. Pre- and post-installation analyses were conducted during an 18-month pilot project from July 2018 to December 2019 (see Appendices A and B for an overview of biogas technology).

The research analyses the impacts on livelihoods and respiratory health. Before and after installation, data was collected on economic efficiency, resource use and health impacts at different levels (individuals, households, local community). The research was designed to answer the following questions:

1. Does biogas provide benefits for households from an economic and social perspective?
2. What measures can be taken to enhance the uptake of biodigesters?
3. What will ensure the financial and social sustainability of community-level biogas businesses?

3. Biogas for households

3.1 Research method

Biogas International Limited (BIL) selected Dunga Beach for this pilot project for its socio-economic profile and its proximity to Lake Victoria, which has an abundance of water hyacinth to use as feedstock. BIL selected the households with the help of a local member of the Dunga Beach Management Unit (DBMU) using criteria including ability and willingness to service the biodigester, neediness in terms of relative poverty and size of household, and vulnerability. Vulnerability was assessed as higher if the household was female-headed or widower-headed, elderly who look after orphaned grandchildren, and/ or if households cooked for sale inside their homes, due to higher amounts of time assumed exposed to potential pollutants from cooking. Householders with means to pay agreed to contribute 5,000 KSh (US$50), approximately 13 per cent of the total equipment cost. About half of the biodigesters were allocated to households considered highly needy, therefore with no cost.

The research team conducted a baseline survey in August 2018 and a follow-up survey in May 2019 for longitudinal monitoring and evaluation, with several additional informal visits throughout the project's duration. Quantitative data was supplemented with observational field notes and discussions to triangulate the findings.

Two associates of the Centre of Development Studies at the University of Cambridge led the monitoring and evaluation of both interventions, working closely with partners from Adoyo Community Consultancy who guided the team with local and cultural knowledge and translation skills, and undertook frequent visits to the site during the project. The research methodology included baseline and endline household surveys (see the baseline study report for initial survey questionnaire[19]); community meetings; key stakeholder interviews with local organisations, non-governmental organisations (NGOs) and government ministries; household visits and site observations; and a review of secondary literature (see Appendix C for research methodology and key stakeholder details). Researchers applied ethics training to data collection and analysis, and participants remain anonymous to protect any sensitive data. Photographs are reproduced with recorded permission from householders.

Both the mixed-method approach and longitudinal surveys offered many opportunities for triangulating the data. Working closely with Adoyo provided a source of information and deeper understanding of local practices and priorities. Repeat visits to the study area established rapport in the community. The main limitation of this research is the limited time frame of observation after the installation of the biogas digesters.

It was important to draw a clear line between observation and support. During interviews, if survey respondents asked for advice about technical aspects of the biodigester, the research team noted questions and passed them to the BIL technical support team. An official from the DBMU acted as a facilitator and organiser for the meetings; this was essential in order to gain access and trust, but may also have impacted on some of the discussions.

3.2 Installation process

Households in this area use charcoal cooking stoves (jikos) and three stone outdoor fires for the majority of their cooking needs. Fifty households agreed to have biogas systems installed as an alternative to these traditional systems (see Figure 2). Four were initially selected as pilot households representing the four main tribal groups in the settlement, allowing people to visit the pilots and see the digesters working before their final decision. Twelve households declined after initial interest and household interviews, concerned about available space, and time and labour to feed the digesters. Others were selected in their place.

Figure 2: Traditional cooking stoves used in Dunga and biogas stove inside household and external biodigester

Charcoal jikos (outside and inside the house) and three stone cooking area

There were two phases for the main rollout: December 2018 to January 2019 and March to April 2019. Thirty-eight households were surveyed before and after installation with a semi-structured questionnaire. Most of the biodigesters in these households had been working for at least three months post installation.

Domestic biogas digester being installed in Dunga Beach

BIL has been installing biodigesters in households for over ten years, and has developed a clear training package to maximise use and post-installation efficiency. Training and information were provided on biodigester function and feeding. In May 2019, most biodigesters were working well, and nearly all households were using the gas for cooking. A few had technical issues, often caused by underfeeding due to limited availability of feedstock or pipes being blocked (more than half of these problems were with the gas pipe or feeder pipe). While most householders wanted more training and checks, the locally trained BIL technicians were considered competent and responsive in nearly all cases.

Domestic biogas digester installed in Dunga Beach

3.3 Impact on fuel use

Most households used cowdung as feedstock, with some using water hyacinth and household waste (see Figure 3). Women are responsible for collecting feedstock and managing bioslurry output in the majority of households. In about a quarter of households these tasks are shared by men, children and grandchildren.

Figure 3: Type of feedstock used for biodigesters in households

	Cowdung	Household waste	Fish waste	Water hyacinth
Number of households using	37	6	6	11
Percentage	97%	16%	16%	29%

Source: May 2019 survey data

Baseline data collection

Adding biogas did not mean it was used exclusively; only two households did this. The rest continued to use charcoal (53 per cent), firewood (34 per cent) and papyrus (24 per cent) or other fuels (23 per cent) as a back-up, in particular for long cooking times or when the biodigester was underfed.

Despite this, there were indications of very significant reductions in amounts of certain fuels used (charcoal use reduced by 45 per cent, wood 83 per cent and papyrus 90 per cent) and the number of households using them (see Figure 4).

We expected household cooking times to reduce, but this was not the case in time observations, although some households reported perceived faster cooking times (see below)– daily average use of 3-stone cooking fires was 1.8 hours, jiko (charcoal) stoves 1.3 hours and biogas stoves 1.8 hours.

Figure 4: Use of fuels for cooking and amounts used by household per week (before and after installation of biogas), May 2019

Use of fuel for cooking	Before (Aug 2018)	After (May 2019)	Change	No. households using before installation	No. households using after installation	Percentage change
Charcoal (gorogoros)	175	97	-45%	36	25	-31%
Wood (bales)	61	11	-83%	27	14	-48%
Papyrus (bales)	49	5	-90%	24	6	-75%
Paraffin (litres)	10	14	+38%	12	3	-75%

Source: August 2018; May 2019 survey data

3.4 Impact on users, and perceptions

Families reported that biogas stoves were **convenient, easy to use and manage, smoke free, clean and hygienic**. In addition, householders reported that the stoves cooked food faster, allowing multitasking and did not dirty the cooking pots with soot. Families were proud of their stoves and noted that visitors also wanted one. All who responded would recommend them where feedstock is available.

Men, children and grandchildren have become far more involved in cooking since the gas stoves were installed. In particular, male involvement has jumped from 9 per cent of households to 31 per cent, reflecting that the stoves are much quicker and easier than starting a fire or using charcoal.

Dunga Beach resident using a biogas stove

3.5 Impact on health, lifestyle and livelihood improvements

Sixty-five per cent of households reported **improvements in health** since the biodigesters were installed, including no more eye pain, fatigue, coughing, headaches or flu, and asthma reduction. A corollary study measured air quality and household pollution in a few of the biogas and non-biogas households locally, and found that **carbon monoxide measurements were significantly reduced** in the biogas households, although particulate matter was little affected.

Livelihoods and quality of life also improved in other areas. One respondent reported that as children no longer have to collect firewood they have time to study (although others have to send their children to find cowdung). Several respondents were pleased that their children could now have breakfast before school, and one was glad to no longer have to collect firewood because of the danger of snakes and other animals.

Dunga Beach residents attending a community meeting with BIL and CISL, September 2019

3.6 Savings and payments for biodigesters

Households reported an average of 64 KSh (approx. US$0.60) saved per day due to fuel cost reductions. Monthly, this amounts to around 1,980 KSh (approx. US$19). These savings are significant in a generally very poor area. However, the average monthly income data was not consistent when compared between the two measurement dates – the amount saved could equate to 10–20 per cent of average household income. Savings data was more easily reported and reliable. Householders reported that money saved through biogas was spent on food and household items, with about a quarter increasing spend on school items and fees, and about a fifth putting it towards savings groups or saving to build housing.

In operation, the only inputs required to the digesters are time and feedstock rather than any ongoing financial commitment. It is interesting to note that none of the households abandoned their digesters over the study period. However, while the digesters are highly economic to run (indeed they create financial savings for their users), the capital required to purchase and install them is significant (approximately US$500 per installation).

The project partners considered carefully whether and if so how to charge households for their digesters. In order to establish a degree of ownership of the technology by households, it was agreed that just under half of the sample would be requested to pay a subsidised rate of US$50, representing a balance between the project's need to roll out the digesters in the community and a recognition that the full cost would be prohibitive for many. It was agreed that the other half of the sample would be exempt from any charge due to their particular needs due to their poverty, age or other forms of vulnerability.

The clear financial savings resulting from biogas deployment as well as the positive experiences of the households in the study has led to many additional families expressing interest in obtaining digesters. A continued subsidy programme or long-term credit offer from a reputable community or private finance provider would enable larger-scale (potentially very large) deployment to take place.

4. Community-level biogas project

4.1 Rationale

Three factors influenced the decision to create a community-level biogas installation at Dunga Beach lakeside. Firstly, exposure to pollutants from biomass and their intensity during cooking are significant health factors. The situation of commercial fish fryers is an obvious opportunity. These women typically spend several hours a day frying fish over open fires or purpose-built fuel-efficient jiko stoves that use biomass; usually in addition to time spent cooking at home with similar fuels. This is a common occupation for women in fishing communities, so lessons learned from this installation could be replicated elsewhere.

Secondly, the feedstock required for the biodigesters could be sourced from water hyacinth. This invasive species causes huge problems in the area, blocking beach access for fishing boats, trade and tourism, and affecting water quality and human health. Mechanical removal is favoured, but to date has been difficult to scale up. Using the hyacinth for biogas production is one way of creating an economic benefit from this activity. Other land-based invasive species could also potentially be used as feedstock.

Thirdly, the lakeside and papyrus wetland area attract educational school trips and local tourists, and is based near Kisumu city. Biogas therefore also has significant outreach and teaching potential.

Fish frying using traditional woodfuel, Dunga Beach

4.2 Aims and set-up procedure

The project aimed to investigate how biogas could be generated and distributed at scale within a local setting in order to become self-sustaining and to test commercial viability. The gas produced was to be sold to the local community of fish fryer women and others, with the aim of supporting those who manage the system.

Community digesters being fed with shredded water hyacinth by BIL's local technicians

After initial discussions with local women fish fryers and others, BIL approached the DBMU, which oversees fishing permits and beach access in the area. The Chiela women and DBMU were familiar with previous biogas projects, and slightly sceptical of the project's ability to make this work where other pilots had failed. The DBMU agreed to rent an area of land at the beachfront to BIL for the construction, next to the women fish fryers' existing cooking area. To work here, the women have to be local to Dunga, and either work independently or be part of the Chiela Women's Group (which owns a fishing boat and an aquaculture fish cage).

BIL installed two 30m^3 'T-Rex' biogas structures that has the capacity to produce 20,000 litres of gas per day. They trained several local technicians to manage the installations, including mechanical set-up, gathering and processing water hyacinth for feedstock, as well as managing bioslurry outputs and interactions with the local community and schools and visitors. BIL worked with the fish fryer group, creating adapted cookstoves to fit the women's larger frying woks. They also discussed payment options and installed individual meters to stoves so that precise gas use could be measured and paid for.

As part of a holistic and adaptive project approach, BIL also created a biogas-fuelled dryer that could be used to preserve and dry fish, vegetables or fruit. BIL technicians added vertical gardens as part of the demonstration area to show how the bioslurry output from the biodigesters could be used for productive vegetable and fruit growing (eg yam, greens, pumpkin).

Example of vertical gardens which have used bioslurry from the biogas digesters

Fish and vegetable dryer using biogas fuel

In the latter part of 2019 the water hyacinth feedstock became unavailable (it is blown seasonally into the area). Adapting to this change, BIL shifted feedstock use to the local invasive species: dodder and prickly pear cactus, chicken factory waste, and restaurant wastes. They have created an additional 28m^3 capacity for the T-Rexes with an additional installation, bringing this to a total of 88m^3 capacity in Sept 2019 which have the ability to produce 50,000 litres of biogas each day.

4.3 Uptake, use and payment

Negotiations with the fish fryer community were delicate, somewhat complex and protracted during the first phase of installation. The Chiela group has influence over their members and has, in effect, a captive market for the biogas in its static location, as it is difficult to capture and transport the gas in an economically viable manner. The women were allowed free use of the gas during the testing and modification stages as the initial stoves were not fuel efficient until modified for their woks.

The technicians recorded daily gas use, time and payments made. Taking an example, over 18 days in September 2019, five women used the stoves 46 times for an average of 1 hour 30 minutes each time (time ranged from 10 minutes to 4 hours 17 minutes). They often paid for the fuel on the same day, but the average delay before payment was just over two days, and occasionally over eight. Overall, users were happy with the gas, but some mentioned that the price was too high.

Commercial fish fryers using community biogas stoves

Two fish fryers had previously stated their average daily payments for wood fuel as 300–500 KSh per day. After a series of negotiations where the women refused to use the gas, BIL gradually reduced the price from 70 KSh/m^3 (pegged initially to be similar to wood fuel costs) to 40 KSh/m^3 – unviable for the business in the long-term. In response to requests from the women, between April and November 2019 BIL tried to charge by gas used and then at a flat rate per hour. Technicians recorded all meter readings and payments. By October 2019, the Chiela group had agreed to pay only 25 KSh/m^3.

As an alternative income source, from August 2019 BIL started selling biogas to a local restaurant, piping it directly at 40 KSh/m^3. They are considering supplying a second restaurant or installing other commercial stoves so that people can cook rice and beans for restaurants in the area. During 2020 demand and income are forecast to increase and BIL estimates that they can meet running costs by the end of 2020. However, commercially viable uptake and scalability cannot be projected with any certainty at this stage so further data will be assessed throughout 2020.

4.4 Benefits for health and livelihoods

From previous reporting we expected the women to spend far longer at the stoves than they did. Typically, they spent less than four hours per day frying fish, often as little as 1–2 hours. The biogas frying process is quicker than using wood fuel as it is an instant heat, however gas flow can fluctuate a little. Using gas also enables the women to fry, then leave the area to undertake other tasks and return later in the day to fry again, as the data showed. Individuals were unable to share how much they were saving in fuel costs.

4.5 Effectiveness for outreach

In the nine months of operation to date, the community digester has received strong interest both locally and further afield, with visits from Kisumu county environment and health officials, many local high schools, Maseno University and professionals working with NGOs on environment and development issues. Situated in a public area, the digester is easily accessible and highly visible. Demand is so high that technicians have begun training local underemployed fishermen and tourist guides to give tours of the facilities. No charge is made for this currently and it has become an important attraction, especially for those interested in environmental issues visiting the papyrus wetland area.

Significant interest in the biogas digesters from local school groups

5. Biogas as an innovation that can support wider development goals

5.1 Innovation of biodigester technology

At the community level, biodigesters are innovative for the fish fryer women in terms of being a new system, using different feedstock, expanding existing knowledge and adapting to local needs (see Figure 5).

At the household level, this is a new technology adapting to specific local needs that introduces a new way of cooking, with men and children becoming much more involved.

Figure 5: How innovative are household and community biodigesters in Dunga Beach?

	Community biodigester	Household biodigesters
Newness	• Two different systems were previously introduced at community level. Both were abandoned within a few years • Using water hyacinth as feedstock; changing environmental problems to solutions	• Biogas household technologies have not been brought into households in this community before
Adaptation	• At community level, the flexible T-Rex biodigester incorporates several improvements on the traditional dome-style biodigester	• The biogas company team is also developing and adapting to the specific peri-urban setting (ie bioslurry waste) and considering additional business opportunities
Interaction	• The community-level biodigester fosters collective action amongst the women fish fryers, and cooperation between the DBMU and the fish fryers. Significant interaction between the biogas company and community users is built into the process of building the digesters	• Household biodigester pilots put in place in July 2018 enabled interested potential recipients to visit and discuss them. During the main installation period a community meeting was scheduled to foster partnership between recipients
Knowledge content	• At community level, several Chiela women were involved in previous training on biodigesters; this innovation will expand this knowledge and introduce it to further individuals	• At household level, recipients will develop new approaches and methods. The biogas company team is also developing and adapting knowledge for the householders
Learning, scaling up and diffusion	• Existing social networks of fish fryers are used for learning in this group • Education visits have markedly increased since the T-Rex was installed • Information is shared with the wider biogas community at conferences and through Kenya Biogas	• The existing close-knit and long-term ties of the Dunga community are essential for sharing learning within pilot households • The expansion potential is as yet unknown • Information is shared with the wider biogas community as part of the learning experience (through CISL, CDS and BIL)

Source: Project discussions and observations

5.2 Contributions towards Sustainable Development Goals (SDGs)

This project's innovative use of biogas contributes towards wider development goals in the following ways:

Figure 6: Project contributions to SDGs

SDG	Project contribution
Goal 1: No poverty	Data is not conclusive but points to improvements in disposable income
Goal 3: Good health and wellbeing	Qualitative data suggests improvements in health for householders
Goal 5: Gender equality	No significant change in levels of women's power and involvement within the community biodigester system (eg no female technicians); however, men are much more involved in household-level cooking and management
Goal 7: Affordable and clean energy	Access to clean energy is improved, and there is a huge reduction in polluting fuel sources despite continued fuel stacking
Goal 12: Sustainable consumption and production patterns	This project, in focusing on using household and environmental waste and invasive species as feedstock, contributes to target 12.4: the sound management of wastes throughout their life cycle, reducing their release to air, water and soil in order to minimise adverse impacts on human health and the environment
Goal 15: Forest management and invasive species reduction	Significant decrease in use of local biomass (wood, papyrus) and imported charcoal Use of invasive species for feedstock may, over time, have a positive impact, but quantities used at present are limited

5.3 Further considerations

Whilst there are not any major issues currently, ongoing bioslurry management in this community is important. Bioslurry is a valuable resource that could be used on gardens. However care must be taken as any unmanaged runoff into the lake could add to the nutrient loading from agriculture and sewage waste, increasing growth of water hyacinth. Plans are under way to use the bioslurry on new vegetable gardens or transport it for use by relatives or in a local gardening project in the Nyalenda suburb of Kisumu. However, this has not yet been formalised.

During 2020 the project will look at the potential for scaling up deployment of the technology. This will be through financially and socially credible business models that could benefit the many lakeside households and fishing communities.

Dunga Beach lakeside clogged with water hyacinth, 2018

5.4 Criteria for success

In comparison with other biogas technologies being introduced in Kenya, several advantages of BIL's approach point to longer-term success in this community:

1. By having skilled technicians leading the project, BIL was able to listen to the women fish fryers' specific requests and adapt the technology accordingly.
2. Balloon technology makes the product mobile. It is placed on the ground rather than being dug in – in a rocky lakeside community, the fixed-dome technologies would not be possible.
3. By training and employing locals as technicians, BIL encourages buy-in from enthusiastic young entrepreneurs who bring an energy and dynamism to the project, developing new ideas.
4. With mobile phone access, people can contact BIL directly for assistance, either locally or from the main office in Nairobi.
5. The demonstration site within 10 minutes' walking distance from the households acts as a central 'hub' for the project. Householders always have support here from a technician for any setup or installation problems.
6. Using the DBMU as an initial 'gatekeeper' ensured that trust was developed more quickly with households. BIL members are not of the Luo tribe, and given recent political unrest between Luo and Kenya's main political parties, local Luo involvement is important for this project – in terms of both language and acceptance of the approach.
7. Finally, setting up a pilot project demonstrated that the proposed solution works. Locals were sceptical as they had seen unsuccessful biogas installations on the beachfront before. The earlier pilots in four households before the main deployment meant that people learned by seeing and doing – key for many in this practical community.

6. Research recommendations

During the course of the study several areas were identified for further research to assist with future programme interventions.

1. This study emerged through **productive cooperation between a University, global corporation, SME and local community**, enhanced by contributions of other stakeholders. This modus operandi offers useful lessons for how complex sustainability challenges can be addressed through multi-stakeholder partnership and could itself be evaluated.
2. **Further air quality analysis** in households and community sites in Kenya could be carried out through the Kenya Biogas Programme, with before and after measurements in situ. This would add to the very scarce data available for air quality in peri-urban and urban areas where other sources of pollutants could influence air quality.
3. **Directly measured health impacts of fuel and household air pollution** are also scarce. In this study, it was not possible to obtain ethical research clearance in time for direct health measurements to be linked to specific households. This would be a valuable addition to reported health benefits.
4. A more detailed study of **long-term adoption and disadoption rates** in different programme models supported by the Kenya Biogas Programme might help improve programme design – for example, whether adoption rates are sustained with more technician input locally, training by locals, community meetings and discussions.
5. A robust **environmental impact study on levels of avoided deforestation** through the use of biodigesters could enable potential subsidies through the wider REDD+ and carbon emissions reduction programmes.
6. Similarly, a **study of the potential impact on the invasive species of water hyacinth** could estimate the potential for productive use and economic benefits.
7. Finally, further discussions with potential sources of financial credit would be useful at local and national level with Kenyan government and private and community based credit and savings schemes.

Appendix A: Overview of biogas technology for sustainable development

Small household-level biogas technology provides access to clean, renewable energy for household cooking and indoor use. Since the 1970s, biogas technology has been promoted as an effective off-grid, pro-poor energy solution in many low and middle income countries.[20] This has historically been regionally concentrated, with about 40 million biogas units in China, four million in India and half a million throughout other parts of Asia.[21] However, while an estimated 18.5 million African households could use biogas technologies, provision within the continent is very low.[22]

More recently, these technologies have been scaled up to provide biogas to a medium-scale provision for the public and private sectors (eg hospitals, prisons, schools and marketplaces).[23]

As a technology, the biogas system is an integrated waste management system producing methane from organic material, and organic digested waste 'biofertiliser' as bioslurry.[24] Biogas digester technology at household level uses animal or plant waste as inputs to 'feed' digesters in an enclosed fixed dome, floating drum or a flexible 'balloon' structure (see Figure 8).[25]

Biogas is produced during the fermentation process of anaerobic digestion of wastes, stored within the digester and then piped directly to cookstoves or into suitable bags. The gas has a range of uses, including cooking, heating, electricity production and for fuelling vehicles. It can be piped directly to point of use or stored as gas or liquid providing an integrated system of energy production, storage and access[6]. The resulting digested waste is non-toxic, being almost pathogen free, according to FAO.[26] It is a stabilised manure and can be used in farms and gardens as a nutrient-rich fertiliser.

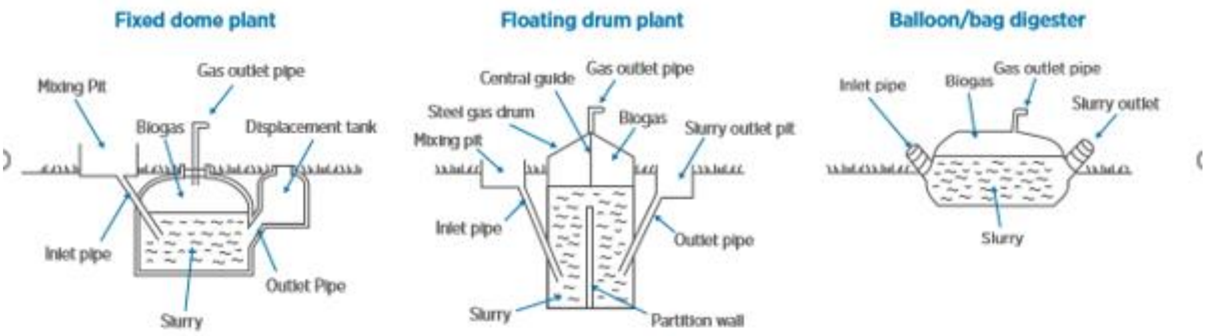
Biogas reduces particulate emissions from cooking[27] and there are other potential benefits beyond energy production for the poor.[28] Health improves as disease burdens are lowered, especially for women and children. Biogas brings economic and social benefits: after initial purchase, biogas can provide a low-cost alternative to other fuel sources, including both capital and operating costs, freeing up income for other uses.[28] In communities where biomass is collected from the local area, time and labour in fuel collection may decrease.

Figure 7: Types of biodigester used worldwide in household applications in developing countries[28]

Type of digester	Description	Regional deployment
Fixed-dome plant	Has an inlet chamber (and, optionally, a lavatory) feeding into the digester which is topped by a dome expansion chamber with a gas release point. A slurry outlet from the digester can feed into a compost pit, providing high-quality fertiliser.	Developed in China, employed in diverse developing countries
Floating drum plant	Consists of two parts: an underground digester and a moving gas-holder. Gas is collected in a gas drum which rises or falls according to the amount of gas present and is kept upright by a frame. Can be used by either a small or medium-sized farm with a digester size of 5–15 cubic metres or in larger industrial agricultural settings with a digester size of 20–100 cubic metres.	India
Balloon/bag digester	A plastic bag is connected to an input pipe, introducing the feedstock, and to an output pipe which removes the slurry. A third pipe at the top of the bag functions as the biogas outlet pipe.	Latin American countries

Source: IRENA, 2016b

Figure 8: Three main small-scale biogas digesters (the balloon digester is used in this project)



Source: IRENA, 2016b

Communities also benefit more widely from the technology's introduction and maintenance, which creates local employment and training opportunities for technicians. Farm yields may increase with use of biofertiliser; or costs of artificial chemical fertiliser (if used) may decrease. Environmentally, forest cover may be maintained and forest degradation lowered when wood is not harvested for fuel or charcoal production. Soil fertility can be enhanced indirectly through not taking wood from the farm areas (leaving biomass and root systems in place); and directly when the effluent (bioslurry) produced is applied as fertiliser to gardens and fields.[29] Carbon emissions may be reduced through a shift away from charcoal and wood fuel: in one study of 358 households in Ethiopia, a shift to biogas reduced greenhouse gas emissions by an estimated 1.9 tonnes of CO_2 equivalent per year per digester installed.[29]

Barriers to deployment – The production potential of domestic biogas has not been fully exploited. In the successful rollout of biogas technology at scale, several challenges remain:[28,30]

1. **Competition from existing (simpler) improved cooking technologies.** There is not enough large-scale conclusive observational data on health impacts of the cleaner and clean fuels, although initial studies suggest biogas and LPG will be much lower in pollutants than improved cooking technologies.[4] Most studies of biogas impact in communities rely on reported perceptions of health changes, which are significant and positive.[31] However, in order to promote biogas at the scales needed as a better alternative to improved cookstoves, decision-makers need conclusive, comparative data on health impacts. There are few reliable studies on changes in indoor air pollution or measured observations of changes in health indicators (eg blood pressure, lung efficiency) as a result of changes from biomass to biogas. And none at large scale. The few studies existing demonstrate a significant improvement in household air quality from the use of biogas for cooking in Uganda.[6] However, they do not reduce household air pollution to below WHO guidelines, potentially due to external ambient air pollution, proximity to other households and use of multiple fuels in households.

2. **Low uptake of technology:** High initial costs coupled with unfamiliarity with the technology stop many poor households from investing.[6] Institutional support for the technology may be inconsistent and insufficient to subsidise and support this deployment on a larger scale. In rural households in central Uganda, adoption rates are 26 per cent of estimated potential uptake.[32]

3. **Post-installation rejection of the technology.** If units are not maintained and technical training is not sufficient, households may return to their previous biomass cooking sources. In some countries up to 50 per cent of biogas plants are not functional.[20] Problems include incorrect feeding of biodigesters, breakdown of equipment, problems with getting enough feedstock, and people's preferences for using traditional or other cooking methods.

4. **Institutional support.** Given the need for clean energy, relatively little attention has been given to the important question of how to enhance the uptake of these technologies at scale.[30] An economically sustainable business model and approach is needed, with necessary government and private support. Fuel subsidies in developing countries tend to be targeted to fossil fuels and are mostly captured by richer households.

Appendix B: The biogas industry in Kenya

Energy solutions for Kenya's population
Demand for wood fuel and charcoal is far higher than supply in Kenya: 35 million tons per year is needed, and supply is 15 million tons per year. Petroleum supplies 80 per cent of Kenya's commercial energy requirements.[33] High oil prices and need for energy security are a driving appetite for alternatives. While household cooking fuels are still largely reliant on solid fuel biomass, there have been significant changes in electricity access and generation. Broadly, Kenya has a low carbon, diverse energy mix in its electricity generation, with geothermal and hydropower significant in its electricity production. Kenya has transformed its electricity generation power sector since 1997, supporting development of renewable energy, and driving what the World Bank calls "one of the most successful electrification programs in Africa", claiming that 75 per cent of households now have access to grid/off-grid options.[34] Kenya has a plan to achieve universal access to electricity by 2022. This is a low carbon and diverse energy mix.

Kenya's new energy policy became law in the Energy Act and the Petroleum Act 2019 after several years' delay. A Renewable Energy Feed in Tariff System will encourage energy generation from renewable sources.[35] VAT exemptions have been offered for some renewable energy components.

Biogas in Kenya
With the first installation of a biogas plant in 1957, Kenya now has several thousand biodigesters supported by national and international organisations. Major public sector development programmes included German development organisation GTZ in the 1980s under the Special Energy Programme in the Ministry of Energy. More recently, Kenya has developed a multi-stakeholder approach in biogas technology dissemination fostered through the Kenyan Biogas Program, part of the wider African Biogas Partnership Program (ABPP).

Since 2009, during its first phase, the ABPP programme has aimed to establish viable biodigester markets, contributing to the achievement of both the Millennium Development Goals (MDGs) and the SDGs through dissemination of domestic biodigesters as a local, sustainable energy source. The programme is based on a Public–Private Partnership model to promote, incentivise and implement 8,000 biodigesters. Partnerships involve government, private sector, non-government and farmer organisations with technical assistance provided throughout SNV.[36]

Under this programme, a raft of small private businesses has grown in Kenya to provide these technologies. Unfortunately, frequent mechanical breakdown, poor installation practices, corruption and malfunctioning systems as a result of lack of training for users led to low confidence and frequent dis-adoption[22] (van Nieuwenhuizen 2018 pers. comm.). Phase 2 of the programme from 2013 onwards has largely addressed these issues by focusing on a) minimum quality standards; b) influencing government policy to support biogas (e.g. reducing high import tariffs for biogas equipment); c) 'de-risking' the technology and generating an improved business case for companies and entrepreneurs, and d) supporting small companies to cooperate to provide a larger scale, more efficient service.

By 2017, 22 marketing hubs had been established linking rural organisations with local construction enterprises and finance institutions. In Kenya, while the business case for farmers has proven viable if they have access to long-term finance, the business case for finance institutions is doubtful due to immature financial markets.[22] At a more local level, community initiatives arrange for the installation of larger volume biodigesters in institutions such as schools, hospitals, universities and energy user groups. At government level, Kenyan national policies seek to increase access to energy and promote the use of renewable technologies. Government has discussed subsidising the biogas industry but has not yet implemented this approach (van Nieuwenhuizen, 2018 pers. comm.).

Appendix C: Research methods and stakeholder interview list

Research subject	Methods	Participant/ Organisation
1. Background and context • Kisumu and Lake Victoria region economy • Fishing community • Political situation, especially Luo culture • Environmental issues • Social and health issues in the area • Kenya economy and outlook	• Literature review (peer-reviewed articles, grey literature and news reports) • Informal and formal discussions in Dunga Beach, Kisumu and Nairobi • Observation	• DBMU • Chiela Women's Group • Ministries of Health and Environment, Kisumu County • HHA/ AZ • BIL • SNV • Maseno University
2. Household-level biogas innovation and application • Biogas innovation research key findings and research gaps • Dunga Beach community history with innovations in biogas • Contact with key stakeholders potentially interested	• Literature review on survey design in relation to alternative energy, health, economic impact, gender implications and labour • Focus groups and community group discussions • Qualitative and quantitative survey • Stakeholder analysis	• 2x community-level meetings for all biogas digester adopters • Chiela Women's Group • Survey of 38 households with biodigesters • Key biogas implementers and researchers in Kenya
3. Community-level biogas innovation and application • Business supply chain for biogas digesters in Kenya • Feasibility analysis	• Literature review on adoption and disadoption rates and reasons, business analysis and feasibility, financing options • Discussion of business approach • Stakeholder analysis and interview	• BIL • Key biogas implementers and researchers in Kenya

Date/ place	Name(s)	Org/ Affil'n.	Subject/contact details
24/08/2018 Dunga Beach	<u>**Dunga Beach Management Unit Project Inception meeting**</u> Maurice Misodhi, Vice Chair Godfrey Ogong, Treasurer Nicholas Didi, Sec. Richard Ojijo, Asst. Sec Charles Apiyo, Sub County Public Health Officer, Kisumu County Project Team: AZ, Adoyo, BIL, Cambridge	DBMU Kisumu Govt	• Inception and introductions • Biogas International Limited and related research component • Health AstraZeneca health screening and referral component discussions
24/08/2018 Dunga Beach	<u>Household Biogas Pilots visit</u> BIL and Cambridge team		• Demonstrating biogas • Some householder comments
27/08/18 Dunga Beach	<u>Chiela Women's Group</u> Nyamenda MENA		• Women's group functions • Biogas previous experience

Date/ place	Name(s)	Org/ Affil'n.	Subject/contact details
27/08/18 Dunga Beach	Dunga Beach Walkabout and Richard Ojiyo DBMU		• Fish frying area/ fisherman observations on declining catch • Conservation Wetland Area • Cage Fishing
5/09/2018 Dunga Beach	Fish trader women	Dunga Beach	• Fish trading and dismal state of business • Biodigester
6/09/2018 Skype	Andreas Wilkes	Unique Forestry	• Expert informant - Gender research on Kenya Biogas • Background on ABPP and other biogas projects
7/09/2018 Dunga	Maurice Misodhi, DBMU and reflections on Dunga	DMBU	• DMBU elections, Dunga social issues • Fishing trip to see wetlands and fish cages
20/09/2018 Skype	David Güereña, and Henry Neufeldt	ICRAF/CIMMYT	Water Hyacinth
10/09/2018 Nairobi	Bert van Nieuwenhuizen Kevin Kinusu,	SNV, ABPP	Africa Biogas Partnership Program, Kenya
10/09/2018 Nairobi	Dominic Wanjehia	BIL	Visit to BIL Nairobi experimental station
14/05/2019	Dunga visit: DBMU meeting with Joel Otieno, Chair Project team Discussion with Mama Zudeya, Chiela Women's group		• Biodigester progress • Chiela women's opinions on community biodigester
20/05/2019	Maseno University and AZ and CAmbs colleagues meeting Maseno: Benson Nyambega Dr Charles Johnson Apuko Philip Guya Absa Sedha Walter Abwao Akeyo Catherine Ndichu AZ: Dr Nelson Otieno, Cambridge: Dr Lia Chatzidiakou, Anika Krause and Dr Natasha Grist	Maseno University	• Biodigester and air quality research • Collaboration opportunities • Health and hypertension readings • Renewable energies
21/05/2019	Veril Ayieko, Kenya Biogas Partnership Program	KBPP	• KBPP focus on households • M&E and checks on deployment • Broaden to markets/industry
29/05/2019	Dunga Household Biodigester Community Meeting Community members biodigester owners and project team	Local	• Progress and situation with household digesters • Discussion about bioslurry • Visit to pilot vertical gardens
29/05/2019	Dr Charles Obonyo, Kenya Medical Research Institute	KMRI	Medical issues relating to pollution from household smoke in Kisumu
31/05/2019	Dr Dickens Onyango County Director of Health, Kisumu	Kisumu County Health	Air quality, disease and pollution in Dunga, Kisumu and Kenya
31/05/2019, Dunga	Biodigester Visit Day (hosted by BIL/Dom Wanjehia) Walter Abwa Akeyo (Maseno)		• Sharing and learning on environment, air quality and health and next steps in Kisumu county

Date/ place	Name(s)	Org/ Affil'n.	Subject/contact details
	Absae Sedah (Maseno) Niklas Wennberg (Hylapond Sweden) Dr Dickens Onyango (Kisumu County Health Dept) Michael Oloko (Jaramogi Oginga Odinga University)		
29/07/2019	Sean Khan, UNEP Kenya	UNEP	• Air quality in Kenya • Further collaboration interest
12/09/2019, Kisumu	Maseno University meeting Maseno University members John Pharoah (CISL) Shirley (Adoyo)		• Collaboration and partnership
13/09/2019, Dunga	Community Meeting, Dunga Beach John Pharoah (CISL), BIL, Adoyo and around 30 residents (all either AQ project participants or biogas users)		• John presented summary of Air quality results • Comments on AQ and Biogas digesters
13/09/2019 Dunga	Observations, Dunga John Pharoah (CISL)		• TRex biodigesters now fuelled by dodder, cactus, restaurant waste and local chicken factory waste (sufficient); expansion TRex 60-88m^3

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