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Abstract

This paper is the outcome of an initial scoping study on the potential for bottled biogas as a clean cooking option for Ghana and Uganda. The study seeks to understand the opportunities for bottled biogas for cooking in Africa, and asks why it has not already taken off, and the key issues to be addressed to enable this.

The paper starts by outlining the nature of the multiple challenges being addressed in the pursuit of clean and modern solutions for cooking, including the health impacts from combustion of solid biomass fuels but also the emissions of GreenHouse Gases. In parallel, developing regions face issues in managing residues and wastes from agro-industry and small-scale farming. Using residues to produce biogas for cooking has a long history in Asia, including at micro scales, typically in household-scale bio-digestors. Biogas is also seen as a bioenergy opportunity for Africa, but many millions of families live in peri-urban areas or for other reasons have insufficient bio-resources to fuel their own digestor.

Bottling of biogas has been suggested as on option for providing accessible, renewable, clean energy to individual households. Research and some pre-commercial trials have taken place in India and parts of Africa, but there is limited evidence in the public domain, and it is evident that bottling has not yet taken off at scale. This study sought to understand the opportunities and the barriers to implementation of bottled biogas for cooking in Africa, with a focus on Ghana and Uganda.

Section 2 of the report reviews anaerobic digestion and biogas production and highlights the technical issues which must be overcome to achieve a bottled biogas product. The current status and potential opportunities for biogas production are reviewed for Ghana (Section 3) and Uganda (Section 4) along with country specific policy support mechanisms. Section 5 reports on field visits to biogas producing sites in Ghana and Uganda in August 2019. Section 6 gives an outline of a workshop and conference organised under this study in October 2019. Section 7 provides overall conclusions of this scoping study and suggests next steps

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Abbreviations

ABPP	Africa Biogas Partnership Programme
AD	Anaerobic Digestion
BOD	Biochemical Oxygen Demand
BSU	Biogas Solutions Uganda Ltd
C/N	Carbon to Nitrogen ratio
CH4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO2	Carbon dioxide
COD	Chemical Oxygen Demand
DM	Dry matter
EFB	Empty Fruit Bunches (palm)
EPA	Environment Protection Agency
ERA	Electricity Regulation Authority Uganda
FFB	Fresh Fruit Bunch (palm)
GHG	Greenhouse Gas
GNCPC	Ghana National Cleaner Production Centre
H2S	Hydrogen sulphide
ha	Hectare
HAP	Household Air Pollution
HRT	Hydraulic Retention Time
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
N2	Nitrogen
NARO	National Agricultural Research Organisation Uganda
NWSC	Uganda's National Water and Sewerage Corporation
OFMSW	Organic Fraction Municipal Solid Waste
O&M	Operation and Maintenance
PKS	Palm Kernel Shells
PMA	Plan for the Modernisation of Agriculture Uganda
POME	Palm Oil Mill Effluent
PSA	Pressurised Swing Absorption
PVC	Polyvinyl chloride
REA	Rural Electrification Agency Uganda
REB	Rural Electrification Board Uganda
RED	European Union Renewable Energy Directive
RETs	Renewable Energy Technologies
RNG	Renewable Natural Gas
SNG	Sustainable Natural Gas
SSA	Sub-Saharan Africa
TCD	Tonnes of Cane per Day
TS	Total Solids
UCPC	Uganda Cleaner Production Centre
VOC	Volatile Organic Compounds

1. Introduction

Global energy consumption has approximately doubled since the 1970s, with an estimated 70% being met by fossil fuels in 2016 (www.iea.org/statistics/). Based on current and planned policy scenarios for energy development, global energy demand is set to grow by 25% by 2040 (www.iea.org/weo2018/). At the same time, concentrations of greenhouse gases (GHGs) in the atmosphere are rising rapidly, with fossil fuel-derived carbon dioxide (CO_2) emissions being the most important contributor and having caused an estimated 1.0°C of global warming above pre-industrial levels (IPCC, 2018). Scenarios for keeping global warming below 1.5°C require a 45% decline in anthropogenic CO_2 emissions from 2010 levels by 2030, reaching net zero by 2050. Limiting global warming to below 2°C requires a 25% decline in CO_2 emissions by 2030, reaching net zero by 2070 (IPCC, 2018). In this context, many developed countries are looking at policies to achieve net zero emissions, and transitioning to renewable energies is a key element in proposals to meet this target. We are also living in societies where the impact our waste streams are having on the environment are of increasing concern, and more efficient use of resources, management of waste and circular economy thinking are among the targets and challenges being considered to reduce the impact we are having on the planet.

The contrast in energy availability, accessibility and energy use is marked between developed and developing countries, with rural communities in many countries still being reliant on traditional fuels (wood and charcoal) for household needs. Whilst the use of traditional fuels may be seen as a contributing factor to global warming, resulting from combustion emissions[1], black carbon emissions[2] and fuel sourcing contributing to deforestation[3], traditional fuel use is also having a significant impact on the health and well-being of those communities which rely on their use. A report by The World Bank (2014) states that ~900 million households in Sub-Saharan Africa (SSA) will still rely on traditional cook stoves in 2020 and that 600 000 deaths per year can be attributed directly to the smoke generated by traditional cook stoves and the fuels used. Further health issues associated with household air pollution (HAP) are also highlighted, and it is reported that globally, HAP-related deaths account for more deaths than HIV/AIDs and malaria combined. The promotion of cleaner, more efficient cooking options for developing countries has for many years focused on improved design of cook stoves still using the traditional fuels. However, alternative energy options including electricity, ethanol, liquified petroleum gas (LPG) and biogas are increasingly being promoted as affordable, clean energy alternatives for cooking in the home. (Appendix 1 and https://www.cleancookingalliance.org/technology-and-fuels/stoves/ for overviews of improved and clean cooking stoves and fuels). The focus of this study is on biogas.

Biogas[4] produced from organic wastes, residues and energy crops has been playing an increasingly important role globally in providing renewable, clean energy. The scale of production of biogas can be entirely flexibly, depending on levels of feedstock and investment available. Raw biogas can be used directly for heating, cooking and lighting at the small scale, or it can be upgraded to biomethane[5], which can be used to replace natural gas

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[1] Combustion emissions from traditional cooking fuels in SSA are reported to contribute 0.4-1.2% of global CO_2(eq) emissions (The World Bank, 2014)

[2] Black carbon emissions from traditional cooking fuels in SSA are reported to contribute 6% of global black carbon emissions (The World Bank, 2014)

[3] The use of traditional cooking fuels in SSA accounts for the consumption of > 300 million tons of wood (including wood harvested for charcoal production) (The World Bank, 2014).

[4] The term biogas is used generically here to refer to the gas derived from biological sources as the result of anaerobic digestion, as opposed to natural gas.

[5] Biomethane is the term used to define methane produced from biological sources, rather than natural gas, and is derived from biogas after scrubbing/purification of the gases obtained from anaerobic digestion.

in gas grid systems, in the generation of power and heat when coupled with an appropriate conversion technologies (e.g. Combined Heat and Power (CHP)), and as a gaseous vehicle fuel (Miltner *et al*., 2017). Biomethane can also be used as feedstock to produce chemicals and materials, replacing methane derived from natural gas (Weiland, 2010).

The potential for biogas production and use at various scales, using various levels of technology, make it an attractive bioenergy option. Due to its versatility, and its ability to address a variety of issues including waste management, renewable energies and climate change, biogas has been promoted in several countries for different reasons (Vasco-Correa *et al*., 2018). The European Union has included biogas as part of its Renewable Energy Directive (COM(2016) 767final/2), the Directive on Alternative Fuels Infrastructure (Directive 2014/94/EU), and as part of it's climate change commitment[6] and it is estimated that biogas will contribute 25% to the 2020 EU-28 renewable energy targets (Miltner *et al*., 2017). However, the uptake and implementation of anaerobic digestion (AD) technologies for biogas production, and biogas use itself, can be challenging, as they are influenced by policy support, socio-economic conditions, technology availability and support, as well as existing infrastructure, location of production and intended use (Vasco-Carrea *et al*., 2018).

China has had a long history of biogas utilisation which, since 2003, has been heavily sponsored through policies and incentives, resulting in considerable uptake of biogas technologies at small and large scale (in 2013 there were 43 million family users of biogas and 10,000 large-scale biogas project) (Gu *et al*., 2016). India has also promoted the use of biogas since the early 1970's in rural areas, through policies promoting off-grid energy and the National Biogas and Manure Management Programme and also implemented a national programme for energy recovery from municipal solid, industrial and agricultural waste in 1995. Mittal *et al*. (2018) have reported that total biogas production in India is 2.07 billion m^3/year, from an estimated potential of 29-48 billion m^3/year. Biogas is also seen as a bioenergy opportunity for Africa, particularly for rural communities where reliance on traditional fuels is prevalent. Roopnarian and Adleke (2018) have reviewed initiatives in several African countries but also highlight barriers to implementation, such as investment costs for digestor systems, understanding of feedstock availability and lack of promotion of the technology.

The existing applications of biogas divide broadly into three categories:

1. Large scale production and upgrading of the biogas to methane, for grid injection or compression and storage and use for natural-gas fuelled vehicles
2. Medium to large scale production, often linked to onsite power generation or combined heat and power (eg at agri-business sites to manage residues and for self-generation, or AD at local authority waste management sites with sale of power)
3. Very small-scale production in household bio-digestors, for providing household cooking fuel, light and heat

The EU's interest is primarily in (1) and (2), as substitute for fossil-based energy. China's and India's experience has been in all three categories, but with a strong focus on the third category, which bring access to energy, including for cooking, to off-grid households. A limiting condition on implementation of such a system is that a household must have sufficient resource for digesting, often a mix of human and animal wastes, food wastes and crop residues. African households with subsistence agriculture, including some livestock, may well meet this

[6] https://ec.europa.eu/clima/policies/strategies_en

resource requirement, and bio-digestors are being actively promoted in some countries. However, many millions of families live in peri-urban areas or for other reasons have insufficient bio-resources to fuel their own digestor.

Bottling of biogas has been suggested as on option for providing accessible, renewable, clean energy to individual households, from biogas production facilities at a larger scale; cylinders or other stores of biogas could be delivered to the home in the same manner as LPG, or Compressed Natural Gas (CNG) (Kapdi *et al*., 2005)). Various researchers in India have explored the potential of adopting bottling techniques for biogas, and implied that there are commercial applications underway (Kapdi *et al*., 2005; Harsha *et al*., 2015; Salave and Desai., 2017). There is limited evidence in the public domain, and the focus of bottling appears to be mainly on fuelling vehicles, with some limited trials for cooking. It is evident that bottling has not yet taken off at scale. There are also clear technical issues which must be overcome to make this a practical solution, most of which will add to the cost of production of the fuel and the affordability to households.

This report is the outcome of an initial scoping study on the potential for bottled biogas as a clean cooking option for Ghana and Uganda.

The study seeks to understand the opportunities for bottled biogas for cooking in Africa, and asks why it has not already taken off, and the key issues to be addressed to enable this.

Section 2 of the report reviews anaerobic digestion and biogas production and highlights the technical issues which must be overcome to achieve a bottled biogas product. The current status and potential opportunities for biogas production are reviewed for Ghana (Section 3) and Uganda (Section 4) along with country specific policy support mechanisms. Section 5 reports on field visits to biogas producing sites in Ghana and Uganda in August 2019. Section 6 gives an outline of a workshop and conference organised under this study in October 2019. Section 7 provides overall conclusions of this scoping study and suggests next steps.

2. Summary of biogas production

2.1 Anaerobic Digestion – feedstock and biogas outcomes

Anaerobic Digestion (AD) is a naturally occurring process in the recycling of organic matter in the environment. In the absence of oxygen, specific categories of anaerobic (putrefactive) bacteria digest organic matter, producing biogas as a by-product of their metabolism. AD may occur in any oxygen depleted environment e.g. water-logged soils (including e.g. paddy fields), water bodies, the digestive systems of other living organisms (Felton et al., 2014), as well as in land-fill and other waste storage systems (e.g. farmyard manure storage, palm oil mill effluent ponds). Managing AD systems can result in energy provision from the methane-rich biogas; a reduction in the volume, mass and toxicity of wastes (as the input substrate); and a beneficial slurry which can be used as a biofertilizer and soil conditioner, to improve crop yields.

The composition of biogas is highly dependent on the organic substrate and the conditions under which the process takes place. The general properties and composition of biogas are reported in Table 2.1 (Raja and Wazir, 2017).

Table 2.1 Typical properties and composition of biogas
Source: Raja and Wazir (2017)

Biogas: odourless and colourless, burns with a blue flame; calorific value of 1 m^3 is ~ 22 MJ (burning at 60% efficiency)	
Material Composition	**Percentage**
methane (CH_4)	50-70
carbon dioxide (CO_2)	25-50
nitrogen (N_2)	0-10
hydrogen (H_2)	0-1
hydrogen sulphide (H_2S)	traces
water vapour	traces
oxygen (O_2)	0-2

The chemical composition of the organic substrate is an influencing factor on the composition of biogas, as well as being an influencing factor on AD conversion rates and yields, and the final composition of the slurry effluent (Achinas *et al*., 2017). The biogas yield of some typical AD substrates used in commercial scale plants in Germany have been reported (Achinas *et al*., 2017) and are illustrated in Table 2.2.

Further substrate specific yields and biogas compositions for individual AD feedstocks are the subject of individual academic studies (e.g. Herout *et al*., 2011) and on-line tools are available which will allow individual feedstock process parameters and yields to be calculated[7].

[7] https://www.nnfcc.co.uk/publications/tool-ad-cost-calculator

Table 2.2 Biogas yield and electricity produced from different potential substrates
Source: Achinas et al. (2017)

Biomass type	Biogas yield per ton of fresh matter (m^3)	Electricity produced per ton fresh matter* (KWh)
cattle dung	55-68	122.5
chicken litter	126	257.3
fat	826-1200	1687.4
food waste (disinfected)	110	224.6
fruit wastes	74	151.6
horse manure	56	114.3
maize silage	200/220	409.6
municipal solid waste	101.5	207.2
pig slurry	11-25	23.5
sewage sludge	47	96.0

**35% electrical efficiency combined heat and power, heating value 21 MJ/m3, 55% methane content, 3.6 MJ/kWh.*

2.2 Anaerobic Digestion process

The chemistry of the AD process has been widely described in literature (Felton *et al.*, 2014; Deepanraj *et al.*, 2014; Zhang, 2016; Achinas *et al.*, 2017; Raja and Wazir, 2017; Roopnarian and Adeleke, 2017) and is summarised in Figure 2.1 and the following section.

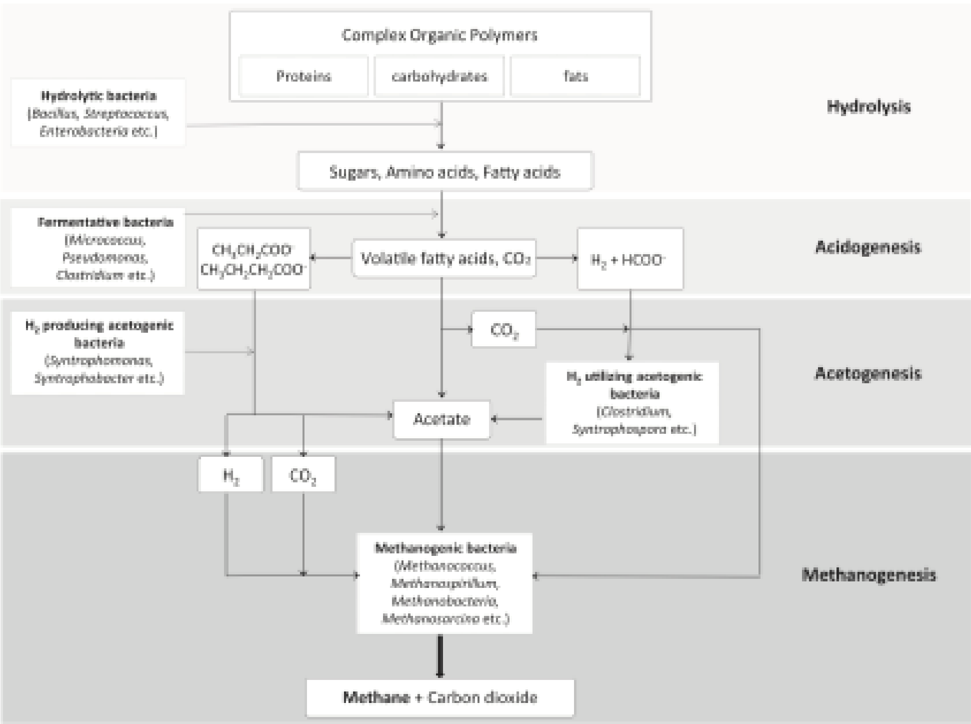

Figure 2.1 The Anaerobic Digestion Process
Source: Roopnarian and Adeleke (2017), modified from Divya et al. (2015)

Anaerobic digestion occurs in four processes which are carried out by various groups of bacteria working together. The basic processes have been described by Raja and Wazir (2017) and are summarised in Table 2.3.

Table 2.3 Biochemical processes of anaerobic digestion
Modified from Raja and Wazir (2017)

Biochemical Process	**Description**
Hydrolysis (or liquification)	Biomass is typically a complex material composed of large organic polymers, proteins, fats and carbohydrates (composition depending on source). In the *hydrolysis* step, these constituents are broken down by fermentative bacteria into smaller, soluble molecules such as amino acids, fatty acids, and simple sugars, making them available to other bacteria involved in the AD process. Hydrogen and acetate are also products of the hydrolysis step and may be used by methanogens in the *methanogenesis* stage of anaerobic digestion process. At the *hydrolysis* stage, many of the molecules may still be relatively large, and are further broken down in the process of *acidogenesis*.
Acidogenesis	The acidogenesis step of AD involves acidogenic microorganisms which further break down biomass and organic products after hydrolysis. The acidogens produce an acidic environment and metabolise amino acids and sugars creating ammonia, H_2, CO_2, H_2S, shorter volatile fatty acids and organic acids, as well as trace amounts of other by-products. The principal acids produced are acetic acid, propionic acid and butyric acid.
Acetogenesis	Acetogenesis is the biochemical process carried out by acetogens resulting in the production of acetate. Acetogens catabolise the products of acidogenesis into acetic acid, CO_2 and H_2. Acetogens break down the biomass to the point where methanogens convert the remaining materials by methanogenisis.
Methanogenesis	Methanogenesis is the final stage of AD whereby methanogens create methane from the final products of acetogenesis, as well as from some of the intermediate products from hydrolysis and acidogenesis.

Deepanraj *et al*. (2014) provide a comprehensive account of the biochemical processes involved in the AD process and summarise the micro-organisms commonly involved in the 4 steps of AD (Table 2.4). The AD process and composition of the raw biogas outcome is dependent on the type of feedstock, most importantly, the carbon (C) and nitrogen (N) content and the C/N ratio (Divya *et al*., 2015). It can also be affected by the presence of toxic compounds which may be present in waste materials (e.g. high ammonia content, soluble copper, zinc, nickel, mercury and chromium salts; pesticides and synthetic detergents). The AD process is also influenced by the composition of the bacterial flora used to initiate the process, which are in turn influenced by process parameters such as temperature (i.e. mesophilic bacteria predominate at 30-40°C whilst thermophilic bacteria function between 50-60°C), pH (i.e. low pH can inhibit bacterial function). Castellano-Hinojosa *et al*. (2018) also provide a detailed review of each of these parameters and reflect how careful consideration should be given to feedstock and AD process design, to make the AD process as efficient as possible, in terms of biogas yield per unit of feedstock. In the context of this review however, the sophistication of technology should be balanced with the practicalities of scale and cost of installation and running costs for AD facilities.

Table 2.4 The 4 process steps of anaerobic digestion and associated bacteria
Source: Deepanraj et al. (2104)

Stage	Type of conversion	Bacteria involved
Stage-I Hydrolysis $(C_6H_{10}O_5)n + nH_2O = n(C_6H_{12}O_6)$	Proteins to soluble peptides and amino acids	*Clostridium, Proteus vulgaris, Vibrio, Bacillus, Peptococcus, Bacteriodes,*
	Carbohydrates to soluble sugars	*Clostridium, Acetovibrio cellulilicus, Staphylococcus, Bacteriodes*
	Lipids to fatty acids or alcohols	*Clostridium, Micrococcus, Staphylococcus*
Stage-II Acidogenesis $C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + CO_2$ $C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2H_2 + 2CO_2$ $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOH$	Amino acids to fatty acids, acetate and NH_3	*Lactobacillus, Escherichia, Bacillus, Staphylococcus, Pseudomonas, Sarcina, Desulfovibrio, Selenomonas, Streptococcus, Veollonella, Desulfobacter, Desulforomonas.*
	Sugars to intermediary fermentation products	*Clostridium, Eubacterium limosum, Streptococcus*
Stage III Acetogenesis $CH_3CH_2OH + H_2O \rightarrow CH_3COOH + 2H_2$ $2CH_3CH_2OH + 2CO_2 \rightarrow CH_4 + 2CH_3COOH$ $CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2 + CO_2$ $CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2$ $CH_3CHOHCOOH + H_2O \rightarrow CH_3COOH + CO_2 + 2H_2$	Higher fatty acids or alcohols to hydrogen and acetate	*Clostridium, Syntrophomonas wolfeii*
	Volatile fatty acids and alcohols to acetate or hydrogen	*Syntrophomonas wolfei, Syntrophomonas wolinii*
Stage IV Methanogenesis $CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	Acetate to methane and carbondioxide	*Methanosaeta, Methanosarcina*
	Hydrogen and carbondioxide to methane	*Methanobacterium formicicum, Methanobrevibacterium, Methanoplanus, Methanospirilum*

2.3 Anaerobic Digestion facilities

The AD process can take place naturally e.g. in landfill and other waste storage sites or within designed small-scale, medium or large-scale reactors. Numerous types of AD systems exist, and the type and design of AD process facilities will depend on the application and scale of the system required (e.g. wastewater treatment, slurry treatment, food waste treatment, solid waste treatment). AD facility designs and the process parameters which affect biogas production are well reported in literature (e.g. Weiland, 2010; Deepanraj *et al.*, 2014; Divya *et al.*, 2015; Zhang *et al.*, 2016; Meegoda *et al.*, 2018) however, it is not the intention of this study to review all types of digestion systems which are available for multiple applications. Focusing on Africa, the two main AD system designs which are often considered are the 'fixed-dome' system, originally developed for use in China, and the 'floating drum' system, developed for use in India. Both of these are often considered for small-scale use (up to 20 m^3 biogas production) or slightly larger community scale facilities. Cost, ease of use and maintenance are important factors in choice of design (see Appendix 2 for comparisons). At the small/household scale, a couple of other AD system designs which have been developed are the 'balloon digestor' and the 'low-cost polyethylene tube digestor', both of which are based on ingenuity and use of low cost, available materials[8] (Morgan *et al*., 2018).

In considering the development of biogas bottling, the scale of biogas production should be a consideration and further techno-economic assessment for specific industrial scale AD designs may need to be future consideration in the continuation of this project. Commercial AD systems are also well documented in literature and have been summarised by Rupf *et al*., (2016) among others (Table 2.5). A study by Roopnarain and Adeleke (2017) reports on the progress made in several African countries, highlighting the scale, application and types of AD systems which have been deployed. Kemausuor *et al*. (2018) report that whilst household scale biogas production systems have been quite widely deployed in several countries in Africa, large-scale operations are limited due to technology constraints, as well as high capital costs and lack of support from institutional and political mechanisms.

Table 2.5 Commercial biogas technologies
Source: Rupf et al. (2016)

Digestor Type	No. of stages	Feedstock TS/DM range	HRT (days)	Operating temperature	Applications
Batch reactors	≥1	<1% (wastewater) or 22-40% (dry)	≥5	Psychrophilic, mesophilic	Wastewater and sewage treatment, OFMSW
Continuously stirred tank reactors (CSTR)	≥1	3-14%	10-30	Mesophilic, thermophilic	Agriculture, livestock, food processing, OFMSW
Fixed film digestors	≥1	<1%	3-5	Mesophilic, thermophilic	Wastewater treatment
Plug flow digestors	1	10-14, ≤45%	20-30	Psychrophilic, mesophilic	Agriculture, livestock

**TS- Total Solids; DM – Dry Matter; HRT – Hydraulic Retention Time; OFMSW – Organic Fraction Municipal Solid Waste*

2.4 Biogas Upgrading and Bottling Technology

Due to the nature of production of biogas at the household scale, in countries such as India, biogas supply is seen to be irregular and its use for cooking is often limited to the site of generation. In cases where excess biogas might be produced, it is unlikely to be transported to other places of demand. Various authors in India have reported on the potential of adopting bottling techniques for biogas, so that production could be a continuous process from generation to distribution, in the same way as CNG (Kapdi *et al*., 2005; Harsha *et al*., 2015; Salave and Desai., 2017).

As previously mentioned, raw biogas is a mixture of methane (CH_4) (50-70%), CO_2 (30-50%), water vapour, hydrogen sulphide (H_2S) and other trace gases. According to Petersson and Wellinger (2009), the calorific value of biogas is in direct proportion to CH_4 concentration and higher proportions of CO_2 and water vapour (compared to natural gas) reduce the energy content/heating value of biogas. The presence of CO_2 also limits the compressibility of the biogas. Other gases which are considered as pollutants of biogas e.g. H_sS, NH_3, volatile organic compounds (VOCs) and siloxanes can be toxic, corrosive or cause problems as the result of their combustion, depending on the end use application of the biogas (Angelidaki *et al*., 2018). In order to address these constraints, it is necessary to eliminate or reduce non-methane gases before compression and bottling.

[8] https://energypedia.info/wiki/Types_of_Biogas_Digesters_and_Plants#Industrial_Digester_Types

The physical and chemical properties of biogas make it impossible to bottle under normal temperature and pressure. As is the case of Liquefied Petroleum Gas (LPG), biogas cannot be converted into the liquid state under normal temperature and pressure. It requires a pressure of about 47.4 Kg/cm^2 at a critical temperature of -82.1^{0}C before it can be liquefied. Compression and bottling of biogas provides an option to improve the quality, energy content, transportability and storage of biogas. The need to upgrade biogas for a wide range of applications has led to the development of specific technologies targeting specific contaminants. Biogas upgrading and bottling technologies have also evolved over time, with different techniques of cleaning, compressing and bottling purified CH_4 gas. The sophistication of upgrading technologies depends on the end use application and may be reflected in the cost of the technology. When upgraded biogas meets the same specification as natural gas, it is referred to as biomethane and more recently Renewable Natural Gas (RNG) or Sustainable Natural Gas (SNG) (Parker *et al*., 2017). Salave and Desai (2017), advise that '*the right choice of the most economically optimal technology is strongly dependent on the quality and quantity of the raw biogas to be upgraded, the desired biomethane quality and the final utilization of the gas, the operation of the anaerobic digestion plant and the types and continuity of the used substrates, as well as the local circumstances of the plant site'*. The following sections provide an overview of biogas purification and upgrading technologies, and compression and bottling technologies, from literature and practical case examples.

2.4.1 Biogas Purification and Upgrading Technologies

The development of biogas purification technologies are well documented in literature by e.g. Kapdi *et al*. (2005); Petersson and Wellinger (2009); Sun at al. (2015); Miltner *et al*. (2017); Salave and Desai (2017); Angelidaki *et al*. (2018); Sahota *et al*., 2018), among others. These papers describe the various techniques used to upgrade biogas, giving detailed accounts of the gas separation principles, processes, equipment and conditions required. Angelidaki *et al*. (2018), specify treatments in biogas upgrading i.e. *biogas cleaning,* whereby the toxic, corrosive or harmful biogas contaminants are removed and *biogas upgrading* whereby the calorific/heating value and Wobbe-Index[9] of biogas is improved by the removal of CO_2 and water vapour.

The processes for biogas cleaning and upgrading can be simply classified according to the targeted gases for scrubbing[10] or by the system used for gas separation. Kapdi *et al*., 2005 describe various scrubbing techniques based on targeted gases (CO_2 and H_2S) and include physical or chemical absorption; adsorption on a solid surface; membrane separation; cryogenic separation and chemical conversion (methanation of CO_2). Agarwal and Shukla (2009) describe a system for the removal of H_2S using an acidic scrubbing system based on iron wool, followed by a lime or water scrubbing system for the removal of CO_2.

Scrubbing systems may also be classified according to the absorbents used to remove impurities e.g. Bauer *et al*. (2013) describe water scrubbing, solvent scrubbing, amine scrubbing, pressure swing adsorption (based on porous solids as absorbent), and separately, membrane gas diffusions based on molecular size separation of the gases. Sun *et al*. (2015) also provide a review of technologies, based on the same classifications as Bauer *et al*. (2013) and review further developing technologies, such as in-situ membrane enrichment, hydrate formation and biological methods for biogas upgrading. The paper also provides comparisons between the energy and financial costs for each technology, based on developments at the time of publication (2015) (Appendix 3).

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[9] 'The Wobbe Index is a measure of the interchangeability of fuel gases and their relative ability to deliver energy. It gives an indication of whether a turbine or burner will be able to run on an alternative fuel source without tuning or physical modifications' https://neutrium.net/properties/wobbe-index/

[10] Gas scrubbing is a generic term which is used to describe the removal of gaseous pollutants from a larger gas stream (https://tapc.com.au/gas-scrubbing/)

Sahota *et al*. (2018) describe biogas purification technologies based on the mechanisms of separation i.e. absorption, adsorption and physical separation. Absorption technologies are based on gas: liquid diffusion, whereby the separation of gases occurs as the result of their relative solubility in the chosen solvent. Absorption technologies are further defined as physical absorption based on water or organic solvents and chemical scrubbing, based on a chemical interaction with the liquid solvent. Adsorption technologies are defined by the interaction (adhesion or binding) between selective components of the gaseous mixture and a solid material. The type of interaction (physisorption or chemisorption) further defines the separation technology, as the result of the process of absorbent regeneration i.e. by pressure swing absorption, purge gas stripping, electrical swing, temperature swing or displacement desorption. The third classification of biogas purification as defined by Sahota *et al*. (2018) is physical separation as the result of selective permeation of gases through a membrane, based on the molecular size of gases and chemical affinity to the membrane, when a pressure/concentration gradient is established. Different types of membranes have been studied for separation, including inorganic membranes, polymeric membranes and mixed matrix membranes.

A number of emerging technologies have also been reviewed, including cryogenic biogas upgrading, which involves the separation of gas mixtures by fractional condensation and distillation at low temperatures, and in-situ methane enrichment. The development of the 'industrial lung' and biogas upgradation through supersonic separation are methods which are underdevelopment (Sahota *et al*., 2018). Table 2.6 provides a review of the advantages and disadvantages of biogas upgrading technologies and a summary of biogas upgrading processes can be found in Appendix 4.

Table 2.6 Comparison of biogas upgrading technologies
Source: Sahota et al. (2018)

Methods	Basis of Operation	Absorbent/adsorbent	Purity of CH_4 (%)	Methane Loss (%)	Energy consumption (kWh/Nm^3)	Cost (€/year) for 1000 m^3		Advantages	Disadvantages
						Investment	Maintenance		
Water scrubbing	Physical absorption	Water	95–98	<2, medium	0.2–0.5	10,00,000	15,000	● No pre-cleaning required ● Simple in operation ● Economical ● High methane purity ● Less methane loss	● Requires huge amount of fresh water ● Use of chemicals ● Chances of biological contamination ● External heat required for regeneration
Physical absorption	Physical absorption	Organic solvents, polyethylene glycol	93–98	<4, high	0.10–0.33	10,00,000	39,000		
Chemical absorption	Chemical absorption	Amines (MEA, DMEA), Alkali solutions	>98	<0.5, low	0.05–0.18	20,00,000	59,000		
Pressure swing adsorption	Adsorption	Molecular sieves	>96–98	<3, medium	0.16–0.43	17,50,000	56,000	● Dry process ● No chemical usage ● No water demand ● No microbial contamination	● H_2S pre-treatment required ● Complex setup ● High investment cost
Membrane	Permeation	Membrane of polymer of silicone rubbers, cellulose acetate, hollow fibers	90–99	<5, high	0.18–0.35	20,00,000	25,000	● Dry process ● No chemicals ● Compact process ● Low mechanical wear	● Pre-treatment required ● High investment cost ● High energy demand ● Unstable over long term
Cryogenic separation	Multistage compression and condensation	No requirement	99	<0.1, lowest	0.18–0.25	–	–	● Highestmethane purity ● No chemicals required ● Upgraded biogas is at high pressure, thus no further compression is required for vehicular fuel	● High capital and operating cost ● Huge amount of energy required ● Pre-treatment required
In situ methane enrichment	Absorption/desorption	Liquid sludge and air	Upto 95	Upto 8, highest	–	–	–	● Cost effective ● Easy in operation	● High methane loss ● Appropriate for only small scale

The choice and feasibility of introducing a biogas upgrading technology is influenced by a number of factors e.g. substrate composition, biogas composition, scale of AD operation, end use application of the upgraded biogas, requirements of existing infrastructure, cost of biogas upgrading process (installation, energy costs and O&M). A summary of biogas upgrading technologies in Europe by Valorgas (2009) suggests that high pressure water scrubbing is the most suitable for small-scale biogas upgrading as it is low cost for installation and maintenance and gives high yields of high purity biogas. At the larger scale, biogas upgrading is optimised to maximizing methane content and purity, and energy efficiency. Water scrubbing is highlighted for its economic viability vs. cryogenic and chemical absorption techniques which, although providing higher efficiency of upgrading require higher investment however, operational costs may balance out investment costs in larger scale applications for cryogenic and membrane technologies (Sahota *et al*., 2018).

2.4.2 Compression and Bottling Techniques

The underlying principle for compression of biogas is to increase pressure and reduce volume, to improve storage and transport options and to concentrate energy content. It has been established that compression of upgraded biogas is more effective than raw biogas, and various compressor systems exist, which can be used in conjunction with upgrading technologies. Olugusa *et al*., 2014 have provided a review of commercially available technologies suitable for use for biogas compression in Nigeria, citing details from one particular company. According to Davey Compressors Company Ltd. (www.daveycompressors.com), 4 different systems are available commercially (i.e. reciprocating compressors, rotary screw compressors, rotary vane compressors and centrifugal compressors) each of which has its own advantages and disadvantages in terms of cost, simplicity of design, ease of use and maintenance etc.

The type of storage system for biogas will also influence decisions on the type of compressor system required. As highlighted by Kapdi *et al*., 2005 (Table 2.7), different storage systems under different pressures will require more or less robust (and costly) systems for storage, However, if the purpose of the process is to increase access to biogas in a storable, transportable for then higher costs for storage systems should also be taken into account.

Table 2.7 Biogas storage options

Pressure	Storage Device	Material
low (0.138-0.414 bar)	water sealed gas holder	steel
low	gas bag	rubber, plastic and vinyl
medium (1.05-1.97)	propane or butane tank	steel
high	commercial gas cylinders	alloy

2.4.3 Biogas Upgrade, Compression and Bottling Case Studies

Case Study 1

Realizing the high potential for biogas in India and its current underutilization of 10% of the possible capacity, Grassroots Energy Technologies Pvt Ltd (GRE), a private company wholly owned subsidiary of US C-Corp founded in 2015, initiated investigations into various aspects of biogas technology. They identified lack of reliability, labour, instrumentation and knowledge as a limiting factor for the uptake of small-scale plants in rural areas. With large scale plants (600 m^3 per day), the major cause of lack of utilisation was identified as high capital cost and specific location limitations due to the uninform distribution of feedstock. GRE intend to solve these issues through innovative approaches, such as introducing a 100 m^3 plant, with an upgrading facility to improve CH_4 concentration in excess of 90%, as well as improving reliability by using modular and prefabricated biodigesters.

Their technology for removing CO_2 can be seen in Figure 2.3, where an absorption disk stack provides a high surface area to dissolve CO_2 from biogas into water.

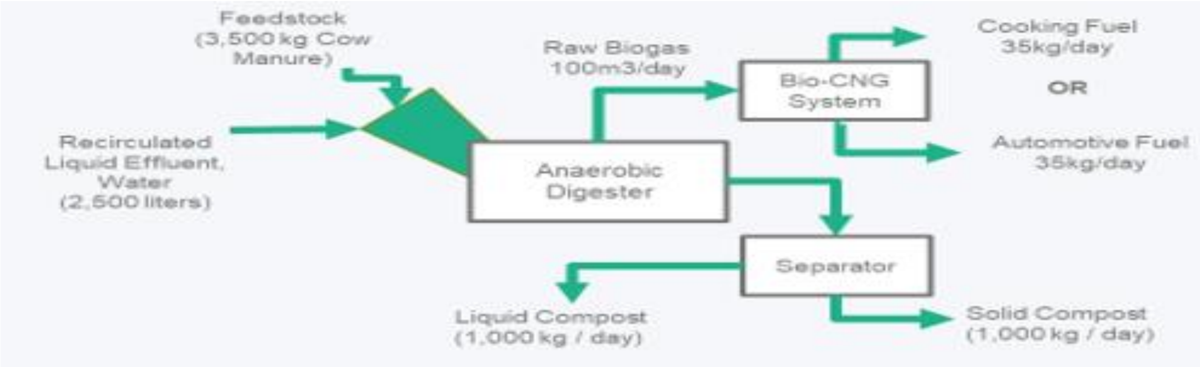

Figure 2.2 Biogas Plant System
Source: https://www.grassrootsenergy.co/

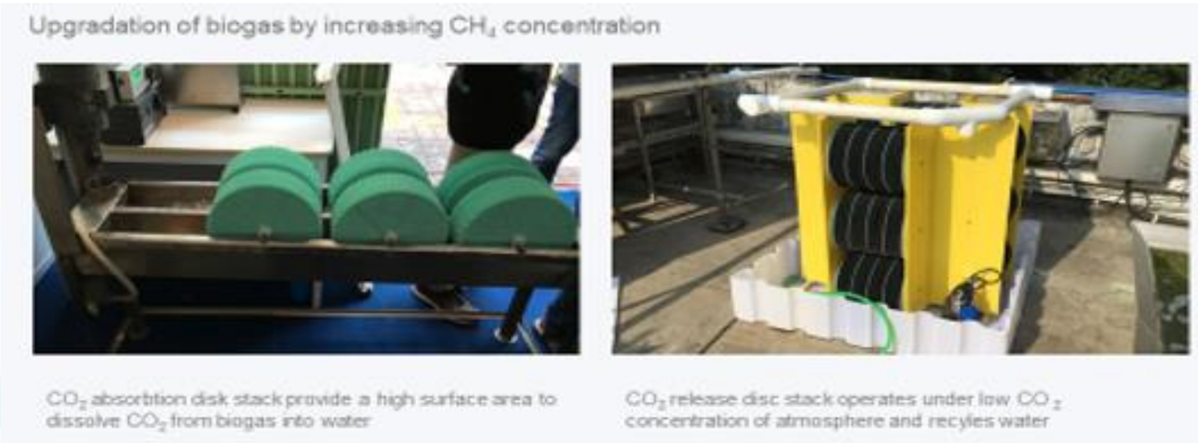

Figure 2.3 Removal of CO_2 from biogas
Source: https://www.grassrootsenergy.co/

The upgraded gas is contained in specialised balloons (under atmospheric pressure) and a CNG filling pump is refitted to compress biogas into cylinder cascades for storage. The compressing facility can be seen in Figure 2.4.

Figure 2.4 CNG compressing facility
Source: https://www.grassrootsenergy.co/

The company indicates that, biogas produced this way competes with LPG with a 25% cut in cost, making the former a potentially preferable choice. They also indicate that CNG could be a better substitute for automotive fuels with a 50% reduction in cost. The developments in these projects have added to the justification for the use of CNG in India and places like Africa, where there is the need to transition to clean cooking fuels.

Case Study 2

The approach taken by GRE's is quite recent, however, it is known that investigations on biogas bottling have been going on in an entrepreneurial mode in India for some years. According to Bamboriya (2012), demonstration projects on medium-size, mixed-feed biogas plants for generation, purification and bottling of biogas, under the Research, Development, Demonstration and Distribution policy of the Indian Ministry of New and Renewable Energy, were developed in 2008-2009. Such installations had the objectives of producing bio-CNG to the same quality as CNG (i.e. 98% methane), to be used as vehicular fuel as well as for solving energy needs for stationary and motive power, electricity generation and thermal applications. The approach was intended to enhance decentralised energy systems, with the backing of sustainable business models. With the Indian Government's financial support, pilot projects were executed in Chhattisgarh, Gujarat, Haryana, Karnataka, Maharashtra, Punjab, Madhya Pradesh, Andhra Pradesh and Rajasthan. An example of the project in Ganganagar, Rajasthan is shown in Figure 2.5. The project proved viable with net profit of 34.92 (Rs. in lakh) and payback periods of 5-6 years and 3-4 years respectively for a non-subsidised and a subsidised case.

Biogas bottling project at Singla Bio-Energy, Vill.–Siaghawali, Teh.-Sadulsehar, Dist.–Sri Ganganagar (Rajasthan)

Figure 2.5 Biogas bottling by Singlar Bio-Energy
Source: https://www.kisgroup.net/biogas-purification.html

2.4.4 Engas UK biogas purification technology – an opportunity for Ghana and Uganda

For this clean cooking project, the availability of feedstock is one of the determining factors for the selection of suitable technology for biogas purification for its scale of operation, modularity, initial investment, and risk mitigation for the continuation beyond the grant-funded phase. Various conventional biogas upgrading technologies have been discussed as above, but finding the right kind of technology in the context of Ghana and Uganda is of vital importance.

There are various biogas purification technologies available in Europe and other countries, where gas scrubbing technologies are required for other industries. However, whether an existing European technology will be suitable in Ghana and Uganda is subject to further investigation; for example ,the technology might require local customization for warmer climates (e.g. cooling instead of heating), and also changing the construction material specification from stainless steel to other, lower-cost materials to make cost targets viable. This may well require some local manufacturing and re-developmental work. As a start, the publicly available information on European products on their quoted capital cost, servicing cost, required minimum-gas-flow rate, and being susceptible to the impurities of raw biogas, are considered in the given context. For example, a typical 100 – 500 Nm^3/h raw biogas upgrading plant from European suppliers (e.g. Greenlane, DMT, Air Products, Parker etc) would cost from £900,000 to £1300,000 per plant. The challenge however would be to produce and supply 500 Nm^3/h raw biogas consistently for a period of 15-20 years.

Looking at this market challenge and opportunities in the context of developing countries, Engas UK Ltd (based in Horsham, West Sussex), has developed a new kind of water scrubbing system. Unlike the conventional water scrubbing system, Engas UK has combined biogas compression, scrubbing and gas-drying into one single step to purify biogas, compress and dry bio-CNG; this innovation has enabled significant reductions in the capital cost, and is more energy efficient.

Conventional Water Scrubbing technology

In conventional water scrubbing systems, the raw biogas is first compressed to 8-9 bar, using a separate centrifugal compressor/screw compressor. This pressurized raw biogas is fed in at the bottom of a 13-14 m tall scrubbing tower, while high pressure water (8-9 bar) is trickled down from the top of the tower through a packing medium, to allow contact between the rising gas flow against the downward flowing water. Water soluble gases (e.g. CO_2, H_2S, NH_3, siloxanes) are absorbed in water under 8-9 bar pressure leaving behind methane (CH_4), which has significantly reduced solubility in water in this condition, compared to CO_2. Pure and wet methane leaves from the top of the scrubbing tower towards a gas dryer.

CO_2 laden water along with other gases (H_2S, NH_3, siloxanes and some CH_4), is released at the bottom of the scrubbing tower in a controlled manner, into a pressurised tank (called the **flash-tank**) where the pressure is dropped to around 2 bar, in order to release 3-5% residual CH_4 (due to is lower solubility at 2 bar than 8-9 bar). This CH_4 is also sent to the gas-dryer to separate the moisture and to produce 95-96% pure dry methane (bio-CNG, biomethane) for immediate use or for further compression.

The flash tank plays a vital role in conventional water scrubbing systems, to prevent a significant loss of methane (around 7-9 %) from the system. The operational and control of this flash tank is fairly complex, requiring fine adjustment of flow rates for both gas and liquid, controlling liquid level, pressure, rate of gas purging etc.

After extracting methane from the flash-tank, water is then pumped into a degassing tower which is kept at atmospheric pressure. The degassing tower is a tall (10 m) water pipe (about 25-50 cm diameter), packed with pall rings to increase the contact area between gas and liquid. A fan-blower installed at the bottom of the degasser tower injects fresh air through the degasser as a counter flow of falling water from the top. This flash air inside the degasser helps to reduce the partial pressure of CO_2 i.e. helps degassing from water. As a result of this air diffusion mechanism into water, and due to the release of CO_2, the pH level of water returns back to normal (around 6.9-7) for its reuse in the next scrubbing cycle.

To summarise, three separate stages are compulsory in conventional water scrubbing i.e. i) pre-compression of raw biogas, ii) scrubbing of raw biogas using a 13-14 m tall towers including the flash-tank mechanism and degassing tower, and iii) gas drying of biomethane for end use. Due to these multiple steps, a large number of additional parts and equipment (e.g. a separate compressor, gas dryer) are needed, adding to cost and servicing/maintenance. Energy consumption is also high e.g. the dryer needs energy to regenerate the moist drying medium. Due to the height of the conventional water scrubbing plant, it is assembled on site, which generally requires some kind of planning consent.

Conventional water scrubbing systems also require a large gas flow rate (generally greater than 500 Nm^3/h) to be financially viable, which therefore requires a large capital investment, and a large amount of consistent feedstock over a long period. This type of plant seems to be relevant for industrial waste generators for their own use, who can ensure the supply of feedstock to make an investment decision. Sugarcane industries, potato chips makers, large dairy farms, palm oil and bioethanol industries could be ideal customers for large-scale conventional water scrubbing technologies.

Engas UK's biogas purification technology

Engas UK's technology (as shown in Figure 2.6) targets small-medium scale projects which are often greater in number as "potential project sites" than large sites. Indeed, the impact from larger biogas/bio-CNG plants could be greater but to kick-start bio-CNG projects in Asia/Africa, Engas UK has introduced modular small-scale plants first.

Engas UK's technology combines all three stages of pre-compression of gas, scrubbing and gas-drying into one single stage. It has also reduced the height of the conventional scrubbing tower from 13-14m down to 2m, thus Engas' system could be packaged inside a shipping container or could be mounted on a frame or pellet. Engas UK's 1-3 Nm3/h bio-CNG plant is made of HDPE plastic, being light weight, corrosion resistant, and having a small footprint 0.7m x 0.7m x 2.7m height. This is suitable for rapid deployment in the field, or for relocating the plant elsewhere, thus potentially having high resale value.

5-10 Nm3/h bio-CNG plants are also available from Engas UK as shown here, which could either be made of HDPE plastic cylinders or by galvanized steel, or by a combination of plastic and metallic cylinders, depending on the availability of local parts and components. Engas UK aims to integrate locally manufactured parts, which is possible due to the flexible designs being adaptable to local specifications, regulations, scale, budget, servicing and maintenance.

Figure 2.6 Engas UK's bio-CNG plant

A schematic diagram is shown in Figure 2.7 as a concept of how various elements of a waste to energy system could be integrated together.

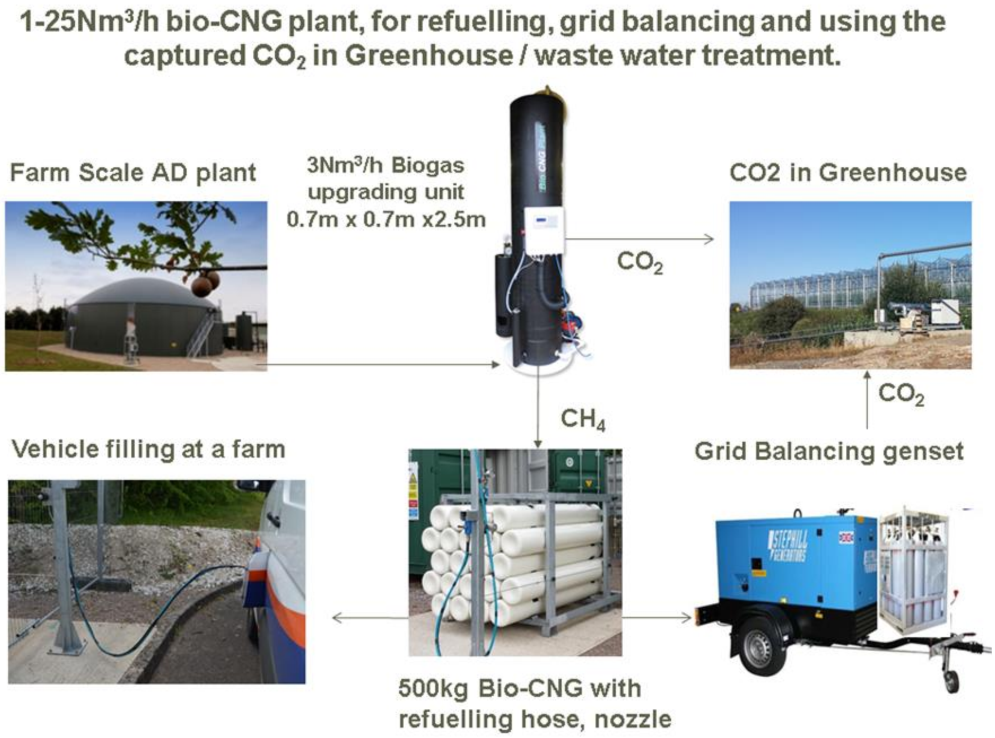

Figure 2.7 Waste to energy system with integrated Engas UK technology

Bio-CNG has the highest volumetric energy density among all gaseous fuels. The cylinders shown in Figure 2.8 will store 500 kg biomethane at 250 bar i.e. about 700 Nm3 of gas or 7000 kWh. This can run conventional domestic gas boilers for space heating for 9 months, at average consumption of 25 kWh/day/house. This will be an alternative heating fuel in farms and off-gas-grid houses.

Engas UKs 25 Nm^3/h plant can produce one cylinder-bank as shown in Figure 2.8 every 2 days for filling smaller cylinders for cooking, hot water in hotels/ industries, refuelling of vehicles, and for back up power to replace diesel generators. Engas UK could supply larger containerised bio-CNG plants in the range of 10-25 Nm3/h raw biogas.

Figure 2.8 Cylinder bank for 500 kg biomethane

Typical customers for this modular scale bio-CNG plants (1-25 Nm3/h) would be University campus, hostels, large hotels, dairy farms, potato chips makers, bakeries, poultry farms, cassava/starch processing industries, palm oil/ bioethanol producers.

Table 2.8 Specification of Engas UK's 25 Nm^3/h bio-CNG upgrader

Biogas Upgrader	Specifications
Raw gas flow rate	25 Nm^3/h
Raw gas specification	50-35% CO_2 ; 50-65% CH_4 500ppm H2S ; <1% oxygen
Inlet gas pressure	7-20 mbar
Outlet biomethane gas pressure	3-5bar; Water Dewpoint: -40^{0}C at 30bar
Outlet gas specification	2% CO_2 ; 97-98% CH4 & C2 hydrocarbons H_2S= 5mg/m^3
Gas upgrading energy consumption	0.3 kWh electricity/ Nm^3 of inlet raw biogas
Water consumption	2lt water / Nm^3 of raw biogas (recycled)
System dimensions	8ft wide x 8ft high x 20 ft long open skid mounted or a 20ft ISO shipping container.
Installation time	Drop, plug and play within 4 hours.

3. Biogas Technology Mapping in Ghana

Following the literature-based technology reviews and case studies above, the partners in Ghana and Uganda undertook research into the current situation for feedstocks, AD implementation and biogas utilization, and initial exploration of potential barriers to biogas bottling, through discussions with key stakeholders.

3.1 Feedstock Resources

Ghana is well endowed with a great variety of organic materials that can be used as feedstock for biogas production. Ghana's economy is strongly oriented toward agriculture, made up of five major subsectors – food crops (59.9%), livestock (7.1%), fisheries (7.6%), cocoa (14.3%) and forestry (11.1%) (MoFA, 2012). These agricultural sub-sectors generate considerable waste which can be used as feedstock for biogas production. Biomass is already a predominant fuel in Ghana, although its current use is mainly in the traditional form, comprising 90-95 percent wood fuels in the forms of firewood and charcoal (Ghana Energy Commission, 2018). Large and untapped biomass resources indicate that Ghana has a lot of bioenergy potential especially for biogas production. A number of scientific studies available indicate availability of biomass resources for biogas production (Duku et al., 2011; Mohammed et al., 2013; Kemausuor *et al*., 2014).

Biomass materials that can successfully be used for biogas production are categorised into two main forms: the first is farm based products such as animal manure, agricultural by-products and farm based wastes; and the second consists of a broad range of suitable organic wastes from the food and feed industries, as well as municipal solid waste.

3.1.1 Residue from crop production

The residue generated from some crops that can be utilized for biogas is shown in Table 3.1. The residue available is dominated by residues from cassava, yam, maize, plantain and groundnut. Together, residues from these five crops constitutes more than 72% of the total residue available. The quantity of biogas that can be generated from both field-based residues and process-based residues were estimated to be 1,600 and 750 Mm^3 CH_4/y respectively, for the 2011 agricultural year. The corresponding energy potential are 57 and 27 PJ/y respectively (Kemausuor *et al*., 2014). Biogas potential from other resources is also shown in Table 3.1. The potential for energy generation from municipal waste in Ghana has been considered for a while because of its potential dual ability to abate environmental pollution problems (Fobil *et al*., 2005), though no project has been implemented yet. Table 3.1 indicates estimates of solid and liquid waste production in the major cities in Ghana (Accra, Tema, Kumasi and 8 regional capitals) and the corresponding biogas and energy potential (Kemausuor *et al*., 2014).

Table 3.1: Theoretical biogas potential from various organic waste sources in Ghana
Source: Kemausuor et al. (2014)

Residue type	**Quantity (Mt)**	**Biogas (Mm^3 CH_4/y)**	**Energy (PJ/year)**
Field crop residues	20	1600	57
Process residues		750	27
Wood waste	0.35	19	0.63
Animal manure	2860	100	3.6
Municipal solid	2.1	230	8.4
Municipal liquid waste	0.56	17	0.61
Total	**2,883**	**2,716**	**97.24**

3.1.2 Residues from food processing industries in Ghana

Oil palm processing

Ghana currently has a total of approximately 305,800 ha of oil palm of which more than 80% is cultivated by private small-scale farmers. During the processing of the fresh fruit bunch (FFB), a significant amount of wastewater with high organic load is produced, known as Palm Oil Mill Effluent (POME) (see Figure 3.1). The ratio of POME produced is approximately 0.6 tons per ton FFB processed. Furthermore, empty fruit bunches (EFB) (see Figure 3.2) and palm kernel shell (PKS) (see Figure 3.3) are further wastes generated by the milling process at the rate of 23% and 7% respectively from processed FFB. Table 3.2 presents biogas potential with the corresponding energy potential from some of the largest palm oil processing companies in Ghana. Based on the residues available in these companies 11,755 m^3 CH_4/h is expected to be generated if all the waste is utilized for biogas production.

Figure 3.1: Palm Oil Mill Effluent (POME)

Figure 3.2: Empty fruit bunches (EFB)

Figure 3.3: Palm Kernel Shells (PKS)

Table 3.2: Energy potential from biogas of Oil Palm Processors
Source: Daniel et al (2014)

Company	**Milling Capacity** MTFFB/hr	**POME** MT/hour	**EFB** MT/hour	**PKS** MT/hour	**Methane potential** $[m^3 CH_4/year]$	**Electricity capacity [kW installed]**	
						min	**max**
GOPDC - Ghana Oil Palm Development Company Ltd.	60	36	13.8	4.2	4,101	13120	15,993
TOPP - Twifo Oil Palm Plantation Ltd.	30	18	6.9	2.1	2,050	6560	8000
BOPP – Benso Oil Palm Plantation Ltd.	27	16.2	6.21	1.89	1,845	5905	7200
NORPALM GH LTD.	30	18	6.9	2.1	2,050	6560	8000
JUABIN OIL MILLS	15	9	3.45	3.45	1,025	3280	4000
AYIEM OIL MILLS	10	6	2.3	0.7	6.83	2187	2670
TOTAL	172	103.2	39.56	12.04	11,755	37,617	45,846

Fruit processing

Ghana is a major producer of fruit and vegetables. As most other agricultural products, fruit and vegetables are mainly cultivated by private small-scale farmers with the major commercial production areas located in the southern part of the country where closeness to the ports enhances export trade. While most Ghanaian fruits are exported unprocessed, there are some companies processing mango, pineapple, papaya or oranges locally.

There are few large fruit-processing companies in Ghana. The processing industries generate significant quantities of waste product. Such waste materials can quickly begin to decay, giving rise to decayed materials with bad odour which therefore needs proper treatment and qualifies as feedstock for biogas generation. Table 3.3 presents potential biogas that can be generated from residues generated from the respective large-scale fruit processing companies in Ghana.

Table 3.3: Energy potential from biogas of selected fruit processing companies
Source: Ulrike et al., 2014

Companies	Products	Fruits residues [MT/year]	Estimated methane potential $[m^3 CH_4/year]$	Electricity capacity [kW installed]	
				Min	Max
Blue Skies Ghana Ltd.	Fresh cut-products for export and juice for the local market	8,000 MT for fresh cut residues and fruit waste from juice production	374,000-572,000	160	298
Pinora Ltd.	Juice and concentrate for export from pineapples and oranges	40,000 MT of fruits waste	1,600,000-2,134,000	680	1,110
Fruittiland Ltd.	Juice and concentrate for export from pineapples and oranges	45,000 MT of fruits waste	3,200,000-4,800,000	766	1,249
Peelco Ltd.	Fresh cut-products for export	2,000 MT of fresh cut residues	150,000-250,000	33	68
Total				1,639	2,725

Cocoa processing

Ghana is the second largest producer of cocoa in the world. Currently there are six cocoa growing areas namely Ashanti, Brong Ahafo, Eastern, Volta, Central and Western regions. These growing areas amount to 1.6 million ha of cocoa farming land with a production of about 870,000 Mt cocoa beans as a key product. The cocoa pod produced after the removal of the cocoa beans from the fruit, is one residue that could be a potential feedstock for biogas plants. The pod forms about 66 - 70% of the weight of the fruit (Adzimah and Asiam, 2010). Based on estimates of cocoa production in Ghana, about 2 to 3 million tonnes of dried pod could be available annually on Ghanaian cocoa plantations. However, utilizing pod husks as a substrate for biogas is yet to be investigated. Besides, the widespread nature of cocoa-processing sites and smallholder farming make it difficult and expensive to collect and transport the cocoa pods to sites of utilization. The utilization will also depend on logistical and economic factors

Table 3.4 shows the main processing companies in Ghana of which cocoa shell capacity is known and might be a source for energy generation through biogas. The volumes of cocoa bean shells of other big processing companies, such as Nestle Ghana Limited, Cadbury Ghana Limited, are not known but could be in the same range of between 3,000 and 6,000 MT per year (Ulrike *et al.*, 2014).

Table 3.4: Energy potential from biogas of cocoa processing companies
Source: Ulrike et al. (2014)

Companies	Production Location	Cocoa bean shells Mt/year	Estimated methane potential $[m^3 CH_4/year]$	Electricity capacity [kW installed]	
				Min	Max
Barry Callebaut Ghana Ltd	Tema	Up to 3,000	500,000	213	260
Cargil Ghana Ltd.	Tema	Up to 6,000	1,000,000	427	520
Cocoa Processing Co.Ltd	Tema	Up to 3,000	500,000	213	260
Niche Cocoa Industry Ltd.	Tema	Up to 3,000	500,000	213	260
ADM Cocoa (Ghana Ltd.)	Kumasi	Up to 3,000	500,000	213	260
Plot Enterprise Ghana Ltd.	Takoradi	Up to 5,500	900,000	384	468
West African Mills Co. Ltd.	Takoradi	Up to 5,000	820,000	350	426
Total				2,013	2,454

Starch Production

Ghana is the third-largest producer of cassava in Africa after Nigeria and the Democratic Republic of Congo with a production capacity of 14,240 Mt in the year 2011. The only large-scale starch production company in Ghana is the Ayensu starch Company. Besides this there are a number of medium and small-scale companies which are into cassava processing across the country, particularly in Brong Ahafo and Volta regions.

These companies generate quite a considerable quantity of residues (see Figure 3.4) which can be utilized as feedstock for biogas. The Ayensu Starch Company (ASCO) was established in 2003 by the Ghana government in an attempt to commercialize the cassava produced in the country. The factory has a capacity to process 22,000 tonnes of cassava starch every year to feed local (multi-national) industries in Ghana. The production process generates wastewater including a pulp, which needs adequate treatment but is more likely to be discharged uncontrolled. For every per ton of cassava starch produced, approximately 15.6 m^3 wastewater and 5.6 tonnes pulp is generated, which can be used as feedstock for biogas plants[11]. Cassava residues have the potential of producing 6,133,000 m^3 CH_4/yr of biogas.

Figure 3.4: Burning of cassava peels at cassava processing site in Brong-Ahafo region

[11] Factory manager at the starch plant

Livestock farming

Considering the population of the five main livestock groups in Ghana and the estimated dung per head, the potential amount of manure that can be produced from the respective livestock in the country would be as shown in Table 3.5. Table 3.5 also presents the respective biogas potentials as well as the corresponding energy potential from these wastes.

Table 3.5: Energy potential from biogas of manure produced by livestock in Ghana
Source: MoFA (2013); Larson and Kartha (2000)

Type of Livestock	**2010** ('000)	**2011** ('000]	**Est.dung per head kg**	**Dung produced daily in 2011 Mt/d**	**Estimated methane potential** $[m^3 CH_4/year]$	**Electricity capacity [kW installed]**	
						Min	**Max**
Cattle	1,454	1,498	12	17,976	119,086,506	50,810	61,925
Sheep	3,759	3,887	1.2	4,664	54,305,284	23,170	28,239
Goats	4,855	5,137	1.5	7,706	89,724,811	38,283	46,657
Pigs	536	568	3.6	2,045	24,632,025	10,510	12,809
Poultry	47,752	52,575	0.02	1,052	17,509,488	7,471	9,105

Abattoirs and slaughterhouses

The Accra and Kumasi Abattoirs are the largest in Ghana and have been equipped with modern facilities. Both have maximum capacity to slaughter 450-480 cattle per day, 450-480 sheep and goats per day and 200 pigs per day.

Table 3.6: Energy potential from biogas at abattoirs in Kumasi and Accra
Source: Ulrike et al. (2014)

City/year	**Type of animal**	**Average Per month**	**Content per animal**		**Estimated methane potential** m^3 CH_4/y	**Electric capacity (kW installed)**	
			Paunch kg	**Blood kg**		**Min**	**Max**
Kumasi Abattoir	Cattle	7,000	12	15.8	62,730	27	33
	Sheep	1,600	1.6	2.1	1,910	0.8	1
	Goats	1,900	1.6	2.1	2,270	1	1.2
	Pigs	475	4.4	5.8	1,560	0.7	0.8
	Total				68,470	29	36
Accra Abattoir	Cattle	1900	12	15.8	17,030	7.3	8.8
	Sheep	275	1.6	2.1	330	0.14	0.2
	Goats	475	1.6	2.1	570	0.24	0.3
	Total				17,930	8	9

3.2 Business Opportunities in the Ghana Biogas Sector

The market for biogas establishments can be found fundamentally in small-scale applications for institutions (prisons, hotels, and schools), industries and communities where biogas can be utilized for cooking and lighting. There is ongoing research into the development of biogas in Ghana. The following market segments provide opportunities for small-scale interventions and SME involvement.

- Design and installation of agricultural waste-to-energy or feed stock to energy systems for Oil Palm plantations, food/fruit processing and packaging Companies – Consultancy, technology options (Anaerobic digestion), motors, components of biogas plants, Engineering, Procurement and construction (EPC) contractors.
- Biomass fired cogeneration plants for companies near biomass resources – Technology options, motors, components, consultancy, Engineering, Procurement and construction (EPC) contractors, maintenance & servicing;
- Biogas lanterns and generators for rural communities – sale of equipment components to landlords and estate companies with biogas digestors;
- Wastewater/effluent/sludge to energy by anaerobic digestion from Starch factories, brewery etc. – Consultancy, Technology options, motors, components, Engineering, Procurement and construction (EPC) contractors, maintenance and servicing
- Extraction, Cleaning, storage and use of Landfill gas from various open dumps for energy and electricity – Research, Design and testing
- Combined Faecal Sludge and Municipal Solid Waste to Energy systems – Design, research, testing, technology options.

3.3 Stakeholders in the Ghana Biogas Industry

The 'Biogas Association of Ghana' was established about three years ago to manage the affairs of the biogas industry in Ghana. Its objectives are to carry out, encourage and support research into the biogas technology and to ensure the development of quality standards by training actors in the industry based on modern approved practices. The Association was instigated by the Environmental Protection Agency (EPA), the Ghana National Cleaner Production Centre (GNCPC) and the Energy Commission. The main work of the association is categorized under four sections. These are:

- DESIGN AND CONSTRUCTION OF BIOGAS PLANTS
  - Promoting standards in design and construction of biogas by members and ensures quality.
- RESEARCH AND DEVELOPMENT
  - Understanding the context of the biogas sector to promote research for policy advocacy and sustainable development
- SALE OF BIOGAS ACCESSORIES
  - Supporting the promotion of biogas accessories that are quality and ensures that the biogas sector accessories are standards
- ADVOCATING RENEWABLE ENERGY TECHNOLOGY AND USERS
  - Encourage Ghanaians to patronize the use of biogas in their daily heating and cooking activities, to help reduce CO2 emissions from the use of traditional biomass.

3.4 Policy and Other Support of the Biogas Sector in Ghana

3.4.1 Biogas Management, Policies and Regulations

Over the last few years, the Government of Ghana has set up various policies, systems and administrative instruments to control the energy sector and advance the improvement of sustainable power sources. Notwithstanding, there is not a particular policy and regulation yet for the biogas business. A bioenergy policy is still being worked on. The Ghana National Cleaner Production Centre (GNCPC) under the Environmental Protection Agency (EPA) in association with the Energy Commission is preparing a Legislative Instrument (LI) for standards/affirmation on the development of biogas plants. The following are the strategies declared to administer biogas energy usage in Ghana.

a. Renewable Energy Act 2011 (Act 832)
    1. Makes provision for the development, management, utilization, sustainability and adequate supply of renewable energy, including bioenergy resources for generation of heat and power.
    2. Provides financial incentives and a regulatory framework that encourages private sector investment in the bioenergy sub-sector.
    3. Addresses the feed-in-tariff scheme, licensing regime for commercial renewable energy service providers and Renewable Energy Purchase obligation.

b. National Bioenergy Policy for Ghana (still under development)
    - Promote the utilization of biomass waste for the generation of electricity and heat.

c. Energy Policy (2010)
    - Provides direction to all energy programmes and includes the 10% target for the contribution of modern renewable energy to the country's energy sector by 2030.

3.4.2 Institutional Framework

Ghana has several institutions which are directly or indirectly linked to managing bioenergy resources, addressing energy challenges, and implementing the Renewable Energy Act. As in most countries, the Ministry of Energy leads policymaking while commissions/agencies serve as regulatory and/or implementing bodies. Institutions involved in biogas development in Ghana and renewable energy in general are:

1. The Ministry of Energy (MoEn): responsible for policymaking and for providing policy guidance to the sector. Accordingly, the MoEn is responsible for formulating, monitoring and evaluating policies, programmes and projects within the energy sector. A Renewable and Alternative Energy Directorate has been established inside the Ministry as part of the commitment to promote the renewable energy sector.
2. The Energy Commission (EC): manages Ghana's utilisation of energy resources as well as advises on energy policy. It also serves as the licensing authority (electricity and gas utilities); it formulates regulations for electricity and gas, promotes energy efficiency and renewable energy, and acts as the official energy adviser to the government.
3. Environmental Protection Agency (EPA): The EPA is the leading public body for protecting and improving the environment in Ghana. It is responsible for regulating the environment and ensuring the implementation of Government policies on the environment.
4. Public Utility Regulatory Commission (PURC): The Public Utilities Regulatory Commission was set up to regulate the provision of utility services in the electricity and water sectors. The PURC also has regulatory

responsibility over charges for supply, transportation and distribution of natural gas services. The PURC is responsible for setting and approving rates chargeable for the purchase of electricity from conventional and renewable energy sources.

5. Standards Board: Ensures compliance with standards and certification for imported equipment.

3.4.3 License Procedure under the Energy Commission

By the provisions of the RE act, any individual/business that desires to take part in the power generation industry must acquire a permit from the Energy Commission before doing as such. For specialist organizations in the Biogas sector they are required to be authorized under the following classifications

1. Wholesale Electricity Supply License: The production of electricity from anaerobic digestion for supply to distribution utilities and bulk customers.
2. Installation and Maintenance License: The installation and maintenance of biogas systems.

3.5 Case Study[12]

3.5.1 Ghana Oil Palm Development Company (GOPDC) biogas plant

GOPDC is located at Kwae in the Eastern Region of Ghana. It has two plantations which are situated at Kwae and Okumaning estates which is about 22500 hectares of oil palm plantations. GOPDC extracts and refines crude palm oil and palm kernel oil. The plant produces on average about 210,000 tons of oil per year. Currently, GOPDC operates the biggest biogas facility in the nation. The Plant cost 4.5 million euros with a payback period of 11 years. The installation of the biogas plant was completed in September 2014, by contractors from South America and funded by GOPDC. The biogas facility comprises a 2 x 10,000 m^3 biogas plant which produces biogas for heat and steam generation in the refinery plant with 1 x 12,000 m^3 biogas storage. The biogas plant produces 18,000 m^3/day. This has displaced the 615,000 litres of diesel that was previously consumed by the plant per year. The plant has a treatment installed capacity of 160,000m^3/POME/year with a Potential biogas production of 4,000,000 NM^3/biogas/year.

Figure 3.5 Effluent from the mill being disposed and channelled into the biogas reactor

[12] Extracted from a Renewable Energy baseline study by the Ghana Energy Commission (2018)

4. Biogas Technology Mapping in Uganda

4.1 General Overview of Feedstock Potential for Biogas Production in Uganda

4.1.1 Biogas feedstock potential from agricultural crop residues

Agriculture plays a significant role in the Ugandan economy, accounting for 24.9% GDP in 2016/2017 (MAAIF, 2018). Farmers in Uganda grow a wide and diverse range of crops and rear livestock at the small-holder and commercial scales. Crop production generates biomass residues in the field, as by-products of growing, and agro-industries generate further residues and organic waste as the result of processing activities. Substantial amounts of residues e.g. rice husks, corncobs, straw, stover, bagasse, stem, leaves, shell, stubble, peel and cane trash are created every year (Table 4.1). These residues are under-utilised and at the field level, residues may be ploughed back into the soil, or left to decompose. Some field residues may be used as animal feed or collected for use as a fuel source for cooking, however, often field residues are simply burned to make way for the next crop. Processing residues e.g. the husks and hulls from rice, coffee and sunflowers also present opportunities as a biomass resource however, it is more likely that they incur disposal costs for the processor (Okello *et al*., 2013).

Table 4.1: Agricultural residues available
Source: Gebrezgabher et al (2016)

Agricultural residue	Annual production ('000 tons/year)
Bagasse	590
Rice husks	23.3
Rice straw	45.55
Sunflower hulls	17
Cotton seed hulls	50
Tobacco dust	2.4
Maize cobs	234
Coffee husks	160
Groundnut	63

4.1.2 Livestock production

Livestock production in Uganda also plays an important role in agriculture and the opportunity for utilisation of waste is considerable. In this case, waste may be considered as the manure generated from rearing live animals, and also as the processing waste from animal culling and processing.

Waste generated from livestock rearing

A study by Owusa and Banadda (2017), details the rise in population of livestock in Uganda (Table 4.2), and estimates the daily output from each livestock sector, in terms of kg of volatile solids/day and the resulting opportunity for biogas production on an annual basis (Table 4.3).

Table 4.2 Populations of Livestock (1000'), 2013 – 2017
Source: Uganda Bureau of Statistics (2018)

Livestock type	2013	2014	2015	2016	2017
Cattle	13,020	13,623	14,031	14,368	14,189
Sheep	3,937	3,842	3,842	4,198	4,445
Goats	14,433	14,011	15,312	15,725	16,034
Pigs	3,691	3,584	3,916	4,037	4,109
Poultry	43,396	44,698	46,039	46,291	47,578

Table 4.3 Estimated livestock manure production and estimated biogas potential
Source: Owusa and Banadda (2017)

Livestock	Volatile solids (kg/day)	Estimated biogas rate (m^3/kg)	Biogas production (million m^3/year)	Calorific value (PJ/year)
Cattle	2.67	0.2	888.21	17.76
Sheep	0.30	0.31	55.83	1.12
Goats	0.33	0.31	191.00	3.82
Pigs	0.59	0.31	85.82	1.72
Poultry	0.1	0.18	37.51	0.75
Total			**1258.37**	**25.17**

Slaughterhouse and abattoirs

A report by AgriPro Focus Uganda (2015) maps the beef sector in Uganda and estimates the national consumption level of beef at 230,000 tonnes per annum, averaging 6 kg/person/year in 2014 (from 2 million slaughtered animals). Kampala accounts for 16% of total beef consumption, estimated at 15, 000 tonnes annually *(Agriprofocus, 2015)*.

There are over 20 slaughterhouses in towns of major districts in Uganda. In Kampala, there are three major slaughterhouses/abattoirs. Kampala City Abattoir is the largest in Uganda and processes up to 1200 carcasses per day (700 cattle, 300, chickens and 200 sheep). Kampala City Abattoir handles about 50% of meat consumed in Kampala and treats 40% of its waste by biomethanation, to generate 10-15 m^3 of biogas per day[13]. Using Kampala City Abattoir as the basis, biogas feedstock from the slaughterhouses in Uganda has the potential to generate over 416.7 m^3 biogas per day (Table 4.4).

Table 4.4 Biogas feedstock potential from abattoirs in Kampala
Source: Ministry of Water and Environment (2013)

Abattoir	Daily throughput (animals)	Estimated average wastewater capacity (m^3/day)
City Abattoir Ltd. Kampala	250-300	200
UMI Ltd Kampala	30-100	50
Nsooba Slaughterhouse Ltd Kampala	150-200	150
Total	430-600	400

[13] Thomson Reuters Foundation: http://news.trust.org//item/20150202164323-00md9

4.1.3 Biogas feedstock potential from agro-processing industries in Uganda

In Uganda, the manufacturing sector is majorly dominated by agro-processing industries, accounting for over 61% of gross output of the manufacturing sector (Uganda Bureau of Statistics, 2010). The key industries in agro-processing include: processing of Meat, Fish, Vegetables Oil & Fats; Dairy Products, Coffee Processing, Grain Milling, Tea Processing, Sugar Manufacturing, Bakery and Manufacture of Other Food Products; Manufacture of Beverages & Tobacco, Cotton Ginning and Manufacture of Textiles and Leather Products. The production processes of agro-industries generate waste and by-products which are potential biogas feedstocks. The following are some of the key agro-processing sub-sectors and their estimated biogas feedstock potential.

Sugar processing industry

According to the Ministry of Trade, Industry and Cooperatives (MTIC, 2016), in 2015 total sugar production in Uganda was 396,315.95. Sugar cane production of Uganda increased from 1.67 million tonnes in 1968 to 3.86 million tonnes in 2017, growing at an average annual rate of 2.95 %. The by-product of sugar production (molasses) is widely used to produce ethanol and the process generates spent wash (vinasse), which is a potential biogas feedstock. A good example is Kakira Sugar Ltd, which use molasses to produce Extra Neutral Alcohol (ENA) and generates biogas from spent wash. There is no data on volume or quantities of spent wash generated from sugar industries in Uganda. However, the available data on molasses generated in sugar factories gives an indicator of volumes of spent wash.

Table 4.5 Molasses generated in sugar industries in Uganda
Source: MTIC, 2016

No	Name of the factory	Crushing Capacity Tonnes Cane per Day	Area Under Cane ha	Final molasses % cane
1	Kakira Sugar Works Ltd	7200	38700	3.6%
2	Mayuga Sugar Ltd	3500	26000	3.5
3	Kaliro Allied Industries Ltd	1650	1800	3.6-3.8
4	Kamuli Sugar Ltd	1250	8150	4.5
5	Seven Star Sugar Ltd	100-200	-	6.0
6	GM Sugar Ltd	1250	1863	4.9-4.5
7	Sugar Cooperation of Uganda Ltd	4200	18896	4.0
8	Uganda Farmers Crop Industries Ltd	150	4643	3.5
9	Hioma sugar Ltd	1000	931	3.5-4.0
10	Kiyanra Sugar Works Ltd	4000	33551	3.3-3.8
11	Ndibulungi Sugar Works Ltd	200	372.6	-

Dairy processing industry

In 2017, milk production in Uganda was 1,614 million litres (UBOS, 2018). According to a press statement by Uganda Dairy Development Authority, about 80% of the total national milk produced is marketed and 20% consumed by the farming households. Only 33% of the marketed milk is processed and 67% is marketed raw. Uganda has about 13 major dairy processing farms processing 532.62 million litres of milk annually (33% of total milk produced). According to Uganda Cleaner Production Centre assessment reports, each litre of milk processed generates 4-11 litres of wastewater. A study carried by Gotmare *et al.*, 2011, an anaerobic sludge blanket reactor, treating dairy wastewater, achieved COD removal efficiency as 87.06%, BOD removal efficiency as 94.50%, and TSS removal efficiency as 56.54%. The average gas production was observed to be 179.35 m^3/day and methane gas conversion was observed to be 125.55 m^3/day, respectively. Similarly, a study carried by Ramesh *et al*., (2012), on the treatability of dairy waste water in a fixed film and fixed bed anaerobic reactor, found that COD reduction is a maximum of 80.88% for a varying influent, COD from 1500 to 4700 mg/l for the OLR of 0.004 kg COD/ m^2/day and HLR of 0.003 m^3/m^2.day. The maximum gas conversion ratio is 0.265 m^3 of biogas per kg of COD removed. With appropriate technology, wastewater from dairy processing is a potential feedstock for biogas generation. Therefore, 2130.48 to 5858.82 million litres of wastewater, with high organic load generated from dairy processing factories, is a potential biogas feedstock.

Fish Processing

Analysis carried out on effluent from fish processing factories found out that the wastewater generated had a high total COD of 12.4 mg/l, solid content of 5,580 mg/l, protein content of 2020 mg/l and volatile solids 95.4 mg/l (Gumisiriza *et al*., 2009). The wastewater from fish factories has high organic load making it suitable for generating biogas.

Table 4.6 Quantities of wastewater from fish factories in Uganda
Source: Gumusuriza et al., 2009.

Number of factories	Urban centre	Number of factories per Urban Centre	Operating factories	Surveyed factories	Wastewater generated
18	Entebbe	4	3	3	252000
	Kampala	6	5	5	423000
	Jinja	4	3	3	298800
	Masaka	3	3	0	na
	Busia	1	1	0	na

4.1.4 Biogas feedstock potential from municipal solid waste

Municipal solid waste (MSW)

As of 2018, Uganda had 55 municipalities and the quantities of solid waste generated in these major towns remains a challenge. Taking Kampala as an example, according to the Global Green Growth Institute (GGGI) Waste Management Policy report (2018), the rate of solid waste generation in Kampala in 2015 was 3,206 tons per day and is expected to increase to 4,739 tons per day by 2030. There are well established solid waste value chains for key solid waste streams such as metals, banana peels, paper, cardboard and plastic. A significant gap in the solid waste management system is for organic waste (i.e. food waste from households). This waste stream constitutes 73% of waste arriving at the landfill, yet it is not being captured for recycling or recovery to any significant degree. (GGGI, 2018). With appropriate technology, the organic waste from municipal solid waste could be bio-digested to produce biogas.

Municipal sewerage

Research shows that sludge in municipal sewerage is a potential biogas feedstock (Arthur and Brew-Hammond, 2010). As reported in OAG (2015), a study conducted by Mott Macdonald in December 2012, on behalf of Uganda's National Water and Sewerage Corporation (NWSC), estimated that by 2014, a total of 238.9 million litres of wastewater would be generated, of which only 8.38 million litres would be collected and treated. This leaves approximately 230.52 million litres of generated sewage uncollected, and therefore not treated (OAG, 2015). NWSC plans to increase sewerage service coverage from 6.4% to at least 30% (NWSC, 2018). The plan to increase sewerage service coverage indicates future increase of biogas feedstock from the municipal sewerage.

4.2 Overview of Current Biogas Applications in Uganda

Most of the biogas establishments in Uganda are household/small-scale anaerobic digestors, operating on animal manure, human wastes, agricultural residues and municipal solid waste (to a lower extent) and utilizing the biogas for cooking and lighting; however, in some cases the gas is now used to generate electricity.

Domestically, biogas is used for cooking, lighting, heating water, running refrigerators, and electric generators. Agriculturally, it is used on farms for drying crops, pumping water for irrigation and other purposes. In industry, it is used in small-scale industrial operations for direct heating applications such as scalding tanks, drying rooms and in the running of internal combustion engines for shaft power needs. The government of Uganda has been building biogas projects at schools, prisons and large farms. Smaller biogas projects are being implemented by NGO's for small scale farmers (Ocwieja, 2010).

Small scale biogas production for household use

Uganda is one of 5 African countries which have been developing national programmes for domestic biogas under the Africa Biogas Partnership Programme (ABPP) programme. Under the programme, Uganda has seen the construction of 7628 domestic biogas plants. During Phase I of the programme, 5000 biogas plants were constructed in 28 districts across Uganda: eight in Western Uganda; nine in Eastern Uganda and 11 in the Central Uganda region (ABPP, 2019). Phase II of the programme aimed to construct over 13,000 plants by 2017. Biogas Solutions Uganda Ltd (BSU) is the National Implementing Agency for the national programme in Uganda and is managing Phase II of the Uganda programme. BSU is exploring the possibility of promoting packing of biogas in PVC bags. According to the programme coordinator at BSU, less attention has been given to biogas upgrading, mainly because of lack of sufficient knowledge, information and technical skills about biogas upgrade and compression into gas cylinders.

In addition to developing the Biogas Construction Enterprises (BCEs), BSU is developing a centralized client service centre to ensure technical and business standards for the biogas sector. This independent service centre will ensure accountability to clients by the BCEs, implement plant coding for quality monitoring and customer service inquiries.

Medium scale biogas production in agro-processing enterprises

In an effort to conform to standards set in The National Environment (Standards for Discharge of Effluent into Water or on Land) Regulations (S.I. No. 4 of 1999), enterprises, especially those involved in agro-processing, have invested in anaerobic digestors with the dual purpose of generating biogas and treating effluent. Generally, the biogas is used in boilers to generate heat for thermal process in processing facilities.

Table 4.7: Some agro-processing enterprises with medium scale biogas plants

Name of enterprise	**Type**	**Capacity of biogas plant**	**Application of biogas**
Nile Breweries Ltd	Brewery	520,835 Nm^3 /yr	Combustion in steam boilers
Kakira Sugar Works Ltd	Sugar	TBE	Combustion in steam boilers
Bwendero Dairy Farm Ltd	Distillery	TBE	Combustion in steam boilers
Sugar Corporation of Uganda Ltd	Sugar	26,097 m^3/day	Combustion in steam boilers

4.3 Business Opportunities in the Ugandan Biogas Sector

Biogas is considered to be a significant renewable energy option, capable of contributing to the energy resource base of the Uganda. The following are some of the key business opportunities for the biogas sector in Uganda, that accrue from wide application of biogas.

Biogas is increasing being promoted by government of Uganda, Non-governmental organisation and civil society organisation and gradually its application in cooking at household level is gaining momentum. However, there are still challenges that limit wide adoption biogas for cooking. These include lack of upfront investment cost, failure to maintain the biogas system. In urbans areas of Uganda there is almost no use of biogas mainly due to limited space to install domestic biogas system, and a lack of service providers that distribute biogas. This provides a business opportunity for enterprises that provide biogas solutions to address the above challenge and tap into the existing market of domestic biogas.

Biogas provides opportunities for agro-processing industries to switch from use of fossil fuel to clean energy. According to UCPC assessment reports, some agro-processing industries in Uganda including breweries, distilleries, and sugar industries produce biogas from their waste streams to generate heat to meet their thermal energy needs. This provides a business opportunity for agro-processing industries including dairy processing, leather processing, edible oil processing, to invest in bio digestion systems to produce biogas that would substitute use of fossil fuel. Discussions with technical people in the agro-processing industries which use biogas indicate that they are generating more biogas than they can utilise. This provide a business opportunity for upgrading excess biogas to biomethane for packaging in gas cylinders or using it CHP to generate electricity to feed into the grid. The waste streams from agro-processing industries provide large quantities of feedstocks for large scale production of biogas that could be upgraded and compressed in gas cylinders or packed in PVC bags.

Generation of electricity from biogas is still limited in Uganda, in spite of the abundant feedstock available for AD in rural areas (in form of livestock waste). The economic analysis done for a small system (biogas to electricity), rendered the investment in such a system very attractive (Okure *et al*., 2016*)*. This demonstrates huge potential for small and medium sized enterprises, especially those in agro-production in areas that don't have access to electricity, to generate electricity from biogas and bio slurry to improve soils for agriculture production.

4.4 Stakeholders in the Ugandan Biogas Industry

The key stakeholders in the Ugandan biogas Industry include the Ministry Energy and Mineral Development which oversees and coordinates the implementation of energy policies and ensure the effectiveness of these activities. Within the Ministry, a Renewable Energy Department is created to specifically focus on the promotion of renewable energy (RE) and RETs. Other government agencies include: the Electricity Regulatory Authority (ERA), to regulate the Generation, Transmission, Distribution, Sale, Export and Import of Electrical Energy in Uganda; the Rural Electrification Agency (REA), which is the secretariat of the Rural Electrification Board (REB).

Other government entities that are key in the promotion biogas technology include National Agricultural Research Organization (NARO), under the Ministry of Agriculture, Animal Industry and Fisheries. Non-governmental organizations such as Heifer International, SNV, amongst others are also promoting the technology.

Notable organizations that are involved in promoting and improving biogas technology in Uganda are indicated in the table below.

Table 4.8: List of organization involved in improving bioenergy technology in Uganda

No	Name of Stakeholder	Classification of Organization	Relevance of Organization
1	Ministry of Energy and Mineral Development	Governmental agency	Policy formulation and regulations, and project implementation
2	UCPC	Trust	Policy advice, and project implementation
3	Uganda National Biogas Alliance	Not for profit	Dissemination and promotion of improved biogas technology
4	Biogas Solutions Uganda Ltd	Not for profit	Dissemination and promotion of improved biogas technology
5	Hiefer International Uganda	NGO	Dissemination and promotion of improved biogas technology
6	Renewable Energy Business Incubator	Not for profit	Biogas business development support
7	Centre for Research in Energy & Energy Conservation	College of Engineering, Design Art and Technology Makerere University; institution of higher learning	Research, development and dissemination of improved biomass technology
8	Renewable Energy Research Group	College of Natural Science Makerere University: institution of higher learning	Research, development and dissemination of improved biomass technology
9	SNV Uganda	Netherland Development Organization	Dissemination and promotion of improved biogas technology
10	Joint Energy and Environmental Project	Non-Government Organization (NGO)	Biogas technology, improved biomass stoves

4.5 Biogas Technology Policy and Regulation in Uganda

The Uganda Constitution 1995 has provisions on equitable development (Article IX), stimulation of agricultural and industrial growth (Article XI) and promotion of energy policies for meeting people's energy needs in an environmentally friendly manner.

The Electricity Act 1999, which set the legal framework for reforms in the Power Sub-sector and the Rural Electrification Strategy and Plan. The act provides a regulatory framework for power generation from small renewable energy sources and the establishment of the Rural Electrification Fund.

The National Energy Policy, published in 2002, spelt out Government's commitment to the development and use of renewable energy resources for both small- and large-scale applications

In 2007, the Government of Uganda published its Renewable Energy Policy for Uganda, for which the overall policy goal is to "increase the use of modern renewable energy, from the current 4% to 61% of the total energy consumption by the year 2017" (Hazelton, 2013).The renewable energy policy provides for the increased use of biogas, which will improve both energy supply and sanitation, in low and middle income rural households. In addition, the Policy provides for the enactment of the legislation to control open burning or disposal of biomass wastes, without extracting the energy content of the biomass. This measure will increase the energy available for use and reduce further deforestation.

The Plan for Modernization of Agriculture (PMA), which has one of its main outcomes as "increased access to and use of electricity" to support on-and off farm economic activities.

Uganda Standard for Design and operation of abattoirs and slaughterhouses has a requirement that large slaughterhouses or abattoirs use biomethanation in handling waste from their operations.

4.6 Case Studies

Case study - Battery charging and agro-processing services on biogas for the Ssese Islands, Uganda. 2014 Sandra Bos

In 2012, FACT decided to invest in a pilot project to test the technical and economic feasibility of the use of water hyacinth for biogas production and improved household energy access in water hyacinth growing areas. The pilot was implemented by GRS Commodities, a Ugandan company active in bioenergy solutions, under the name *"Battery charging and agro--processing services for the Ssese Islands"*. The objectives of the pilot project were to test the technical and economic feasibility of producing biogas from water hyacinth and generating electricity for battery charging. As a secondary objective, the project also anticipated to contribute to reducing the proliferation of water hyacinth on the Lake Victoria by harvesting water hyacinth and waste disposal of animal manure and improving energy access by supplying households with off--grid energy solutions.

The project activities ended in mid--2013. A period of 2 years resulted in a fully installed and operational biogas system. It was expected that the system would run on full capacity and would offer a profitable business. This was not a realistic assumption and will require more time than the planned 2 years. Getting the system operational and creating the intended demand for the energy services turned out to be harder than expected. As demand for battery charging is low, there was no need to become fully operational - this would have led to wasted energy and excessive operational costs. Due to the disappointing demand, the project changed its strategy by including a rice milling service. Over a period of 12 months, a biogas production of 12.38 m^3/day was reached. Generator Efficiency was tested within the project and seems the estimated conversion rate of 1.4 m3/kWh was excessively high. A conversion rate of 1.25 m^3/kWh appears more realistic, resulting in a daily electricity production of 15.47kWh. The sale of slurry is not yet realized. Since biogas production has been so low, the system has not produced surplus slurry at this stage.

The electricity was used to set up a reliable and affordable battery charging service for households that were previously depending on charging stations on the mainland, associated with high prices due to the transportation costs involved and long lead times up to 3 days. Over the course of the project, rice milling was added to the business model as a supplementary electricity service fuelled by biogas. Rice cultivation, indeed, has recently been introduced by the Kanlangala district government and is becoming an increasingly important economic Milling services.

5. Field Visits – 19th-30th August 2019

The UK researcher working on the study, Mairi Black, joined the Ghanaian and Ugandan partners for a series of field visits.

5.1 Ghana

5.1.1 Guinness Brewery, Kumasi (20th August 2019)

The Guinness brewery in Kumasi is part of the Diageo Group and produces several product lines on site, including Guinness stout, Star Beer, Malta Guinness, Orijin and Smirnoff. Brewing on site is from sorghum and maize grown in Ghana, with imported barley and pale malt. The Smirnoff product is blended on site but there is no distillation process taking place. The current AD facility is an Upflow Anaerobic Sludge Blanket Reactor (UASB), with separate mixing and hydrolysis tanks and has been commissioned to address EPA requirements for wastewater, which is derived from the brewing and packing stages in the factory. The reactor is a continuous flow reactor working at 90 m^3/hr of feedstock input. Currently the biogas is not used in any of the processing steps and is flared. Anaerobic sludge is a valuable product which is re-used as a fertilizer (sold back to farmers) and as AD seed for any plants which request it.

The sister plant at Accra has implemented an AD system where the biogas has been used in processing, however due to a limited number of product lines currently running, the biogas is not being used. It is expected that this will change in the future as new product lines are planned.

The current production of biogas at the Kumasi plant is ~1200 m^3 daily and has the potential to replace ~30% of diesel fuel requirements however, the biogas flow rate must be consistent at 60-80 m^3 and would require clean-up before use. There are plans to implement this in the next 1-2 years so there may be an opportunity to pilot clean-up and bottling technology at this site however, as soon as the systems are in place, all the biogas produced may be utilised by the plant for their own energy needs.

Figure 5.1 AD system at Guinness Brewery, Kumasi, including gas flaring system

5.1.2 HPW Fresh and Dry (21st August 2019)

HPW Fresh and Dry are a Swiss company who process coconut, papaya, banana, mango and pineapple into a range of dried fruit mixes and bars. The facility is run to Fairtrade Certification which was reflected by the orderliness of the site and attention to use of renewable energies (Figure 5.2). The factory currently uses dry waste from processing (coconut) and locally obtained cashew nut shells and other dry waste to run a biomass boiler system for heat, as well as solar PV and solar thermal systems. The AD system is utilised for energy but also to adhere to the EPA regulations for effluent treatment. All of the wet waste from processing and all the resulting biogas is used for processing requirements (heat for drying).

The wet waste is shredded and held in hydrolysis tanks for 15 days after which it is pumped into 1 of 2 450 m^3 fixed dome reactors. It is a mesophilic system running optimally between 30-36^{o}C. Temperature and pH are carefully monitored on a daily basis and controlled by the addition of animal manure or urea in extreme conditions. The biogas is cleaned using an activated carbon system but H_2S in the biogas is also controlled in the AD system by adding O_2 to limit its production (leads to more CO_2 production over CH_4 but is the optimal trade off). The boilers for drying are run on a 2-stage system (1st stage diesel and 2nd stage cleaned biogas) and biogas is also utilized in the staff kitchen for breakfast and lunchtime use. A second boiler is run entirely on diesel. The facility is running at full capacity and could make use of additional 500 m^3 of biogas so no excess produced and flared.

Effluent and sludge are treated onsite with wastewater going through traditional cleaning after AD and the sludge from AD is sent back to the fruit producing farms as valuable fertiliser.

Figure 5.2 AD and renewable energy at HPW Fresh and Dry

5.1.3 Aglow Poultry processing facility (22nd August 2019)

The Aglow poultry processing facility is a 3-year-old plant for slaughtering and packing of broiler chickens. The company produce broiler chickens and also laying hens for eggs at 2 separate facilities, nearby the plant but not directly adjacent to. The plant can process up to 4000 carcasses per day at capacity (e.g. at Christmas) but usually would average ~2500/day of 1.5 kg chickens, when running (the company are currently facing significant challenges from cheap exported chicken, chicken feed cost and availability is a significant factor in production costs). From a 1.5 kg bird, waste from evisceration accounts for approx. 30% of total carcass weight and is treated by the AD system, to adhere to EPA regulations; feathers are burned separately as a means of disposal.

The waste is ground up and fed into 2 fixed domes (each of 225 m^3 capacity) and biogas is collected in a balloon for use in the staff kitchen (catering for 71 people for breakfast and lunch). Further biogas is used to heat water for processing, but excess biogas produced is flared once the balloon has reached capacity. The biogas is used in the raw state and no clean up currently takes place. Water effluent is further treated before release into ponds but currently, solid waste from the digestors is not utilised (remains in the AD tank). There is a potential opportunity to trial biogas bottling at this site as the biogas facility is not optimized for other uses. The poultry facility is relatively rural but too far away from e.g. the nearby secondary school to allow piping of the biogas for further cooking use, furthermore, the company expend significant energy on heat required for the 'brooding' stage of poultry production and would be interested to see if biogas could be bottled for transport and use for process heat at their other production facilities.

Figure 5.3 Aglow poultry processing AD facility

5.1.4 Safisana AD facility (23rd August 2019)

Safisana has been set up as a demonstration plant to show how mixed waste can be successfully managed to address waste disposal issues and environmental concerns. The plant was commissioned between 2009 and 2016 and has now been successfully running for 3 years as the result of careful management of all aspects of the AD system. The parent company of Safisana is a Dutch company however, they continue to support the facility as a demonstration plant as currently it is not running profitably (having been set up to mange waste, rather than as an energy system). The plant has a combined CHP system and electricity is sold to the grid at a very favourable rate for Ghana (17.5 c FiT – per kWh). The plant takes a wide range of waste streams which are carefully managed by the waste sourcing manager. The company are looking to optimize the entire system with better use of heat from the CHP system and profitable fertilizer outputs. They are also encompassing additional composting on site to supply a trial growing facility of vegetables and seedling crops to sell back to farmers.

Feedstock comes from 4 main sources: market waste (veg and fruit waste and trimmings); abattoir waste from 4 local abattoirs – specifically the rumen content which is made up of partially digested plant material (no blood or other waste is taken from the abattoirs); industrial waste from local food processing companies e.g. Nestle out of spec inputs and outputs, waste dough, proteins and kitchen waste from processing and staff catering facilities; faecal waste taken from carefully managed facilities – due to the requirements for faecal waste, the supply must be fresh, consistent and free from other contamination – the company has found that this is better controlled at public facilities e.g. well used truck stops.

All feedstock waste is 'free', but the company pay for transport. Seasonal variation of waste compositions can be a challenge and leads to variation in gas production and composition, but this is all carefully monitored by trained personnel in the on-site lab. Waste is sorted and contaminants removed by hand then macerated and fed into the CSTR AD system (60:40 water:solid). The system is a mesophilic system (optimum 31-37^{o}C) carefully monitored to ensure continuous dry matter, temp and pH. The AD tank is a below ground tank (15x35x35 m) producing approx. 15 925 m^3 biogas per day (0.9 kW/m^3). The system produces 50-75% CH_4, 30-35% CO_2 and monitors H_2S production to ensure it does not exceed 200 ppm. Careful monitoring leads to control of H_2S production by adding more O_2 to the system. H_2S measured on the day of the visit was 17 ppm.

The company expect to expand in the next few years based on the functional success of the facility for waste management, but this is not a break-even system. It is unlikely that excess biogas would be channelled to bottling as currently favourable FiT rate means that the biogas is all utilised for electricity production in this demo facility however, this is an interesting model to explore how AD systems as a means of waste management and energy production could be improved to be more profitable and require less support (e.g. companies should pay for waste streams to be managed by companies such as Sofisana).

Figure 5.4 Safisana AD facility

5.2 Uganda

5.2.1 Centre for Research in Energy & Energy Conservation (CREEC), U. of Makere

CREEC is a not for profit organization based at the University of Makere, offering services in rural electrification; energy for productive use; energy for household use; energy efficiency; energy entrepreneurship and energy testing. The centre has state of the art laboratories for biomass and solar PV products and supports a Regional Testing and Knowledge Centre for stove and fuel testing (Figure 5.5). Work on biogas has been previously carried out at CREEC, and Dr. Ogwok is currently involved in a collaborative project with the University of Leeds, looking at ways to manage invasive water hyacinth as a biomass source for AD and biogas production (https://cier.leeds.ac.uk/news/bbsrc-grant-funded/). The project does not currently consider bottling biogas as it is focused on the technical aspects of AD and a novel bioreactor system.

Figure 5.5 CREEC visit and tour of facilities

5.2.2 Visit to Uganda National Livestock Resource Research Institute (28th August 2019)

Eng. Christopher Kato is a well-known figure in the subject area of biogas production and has been working on this area in Uganda, for many years. The Uganda Biogas Alliance pilot facility was developed as an engineering solution to the management of waste, and for the provision of energy, from and to the Institutes research dairy. The pilot facility allows the dairy to work as a closed loop farming system and currently, the energy used of for the dairy is from a combination of AD biogas converted to electricity by a CHP system, with further energy input from a solar PV system and the national grid. The system also has a battery storage system which is capable of running the dairy for 3 days. The system works independently and switches automatically between energy sources, depending on availability and requirements.

The AD system utilises effluent and manure from the dairy facility in a batch feeding system of 2 x 125 m^3 digestions tanks (buried underground to 7m). The mixture is macerated before introduction into the AD tanks and requires no further additives. The mixture remains in the tanks for 80 days and has a gas/effluent displacement system which controls the AD process. The gas is piped to the clean-up facility where locally produced, pulverised charcoal is used in the clean-up system which yields biogas at 97% purity. The biogas is converted to electricity and currently is largely utilised in the dairy however, a recent research initiative has seen the development of a compressed biogas bottling pilot facility. Eng. Kato has developed a business model for his system which makes bottled biogas a cheaper option than the LPG it would replace.

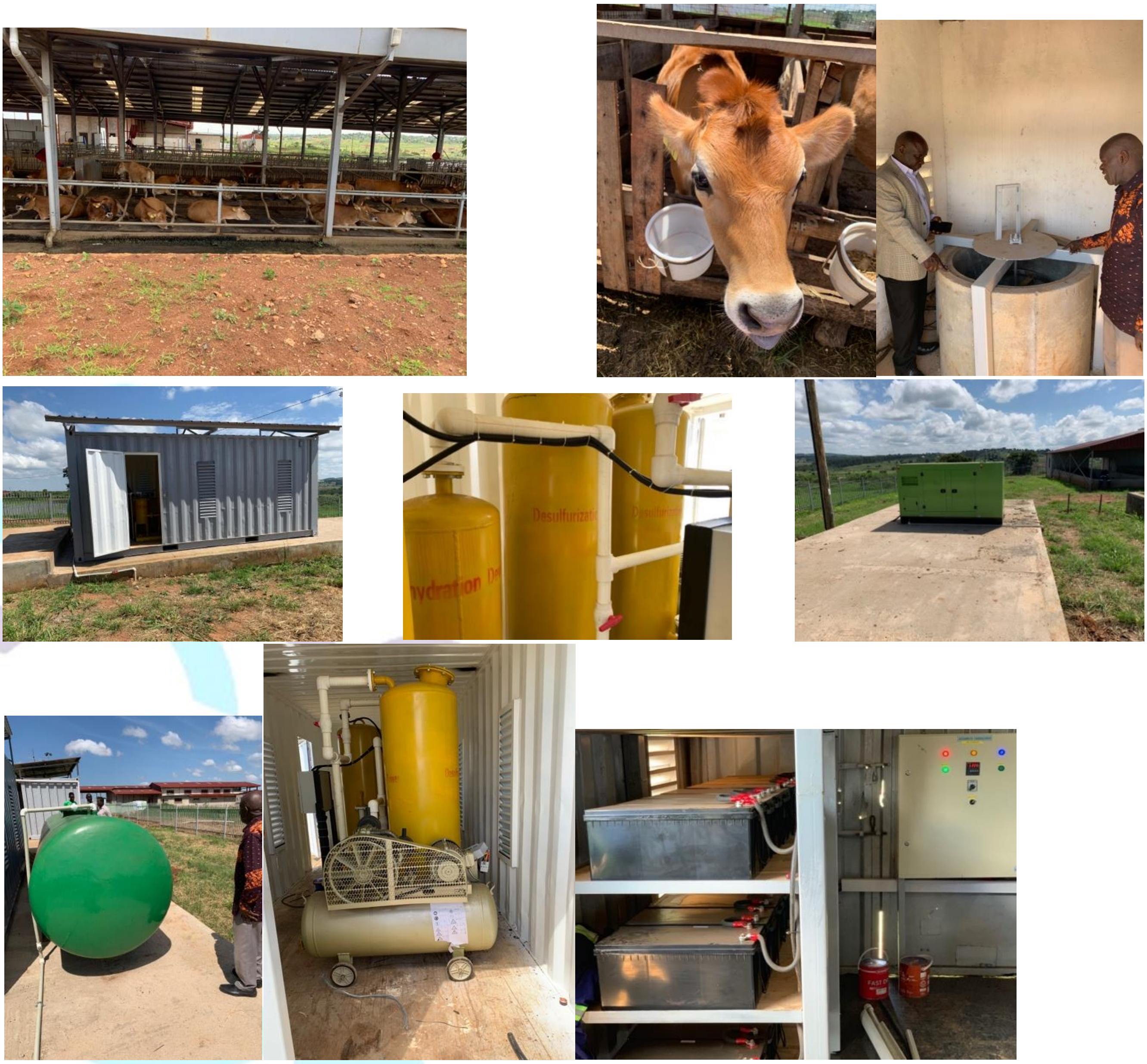

Figure 5.6 Uganda Biogas Alliance Pilot facility

5.2.3 Visit to Bwendero Dairy Farm Ltd (BDF), Hoima (29th August 2019)

The Bwendero Dairy Farm has developed from a dairy facility to a cattle-fattening facility and has recently diversified into an alcohol distillery. The distillery initially utilised cassava and maize as a feedstock, but due to market prices and irregularity of maize supply, the company have now further diversified into sugar as feedstock for potable ethanol production, using molasses and will soon be manufacturing sugar as well as alcohol. The sugarcane is locally grown and sourced.

There AD facility was put in place 3 years ago, to manage effluent from the distillery i.e. spent washings from maize, cassava and now sugarcane. The biogas is used for the production of steam for heat in the distillation process. Steam is also used to supply energy to 2 kitchens which feed the working community 3 meals per day (700 staff) – requiring ~500 kg biogas/month. The biogas is cleaned using a water scrubbing system (to between 50-60% CH_4) and excess is flared if surplus to requirement. The AD system functions according to the distillery production schedule and has not been optimized for biogas production. Currently the system might run on a continuous system at a flow rate of between 12-14 m^3 /hr effluent (producing 642 m^3 biogas/hr) at times of lower distillery production, to 20-25 m^3/hr (producing 1000 m^3 biogas/hr). Effluent from the distillery is stored in large ponds to allow the effluent to cool down and methane can be seen to be forming as the effluent sits in the effluent pool and is also still forming as AD effluent leaves the system. The company are profit focused and keen to optimize costs by improving efficiency at all levels and are very interested in exploring the opportunity of bottling biogas as a new market opportunity.

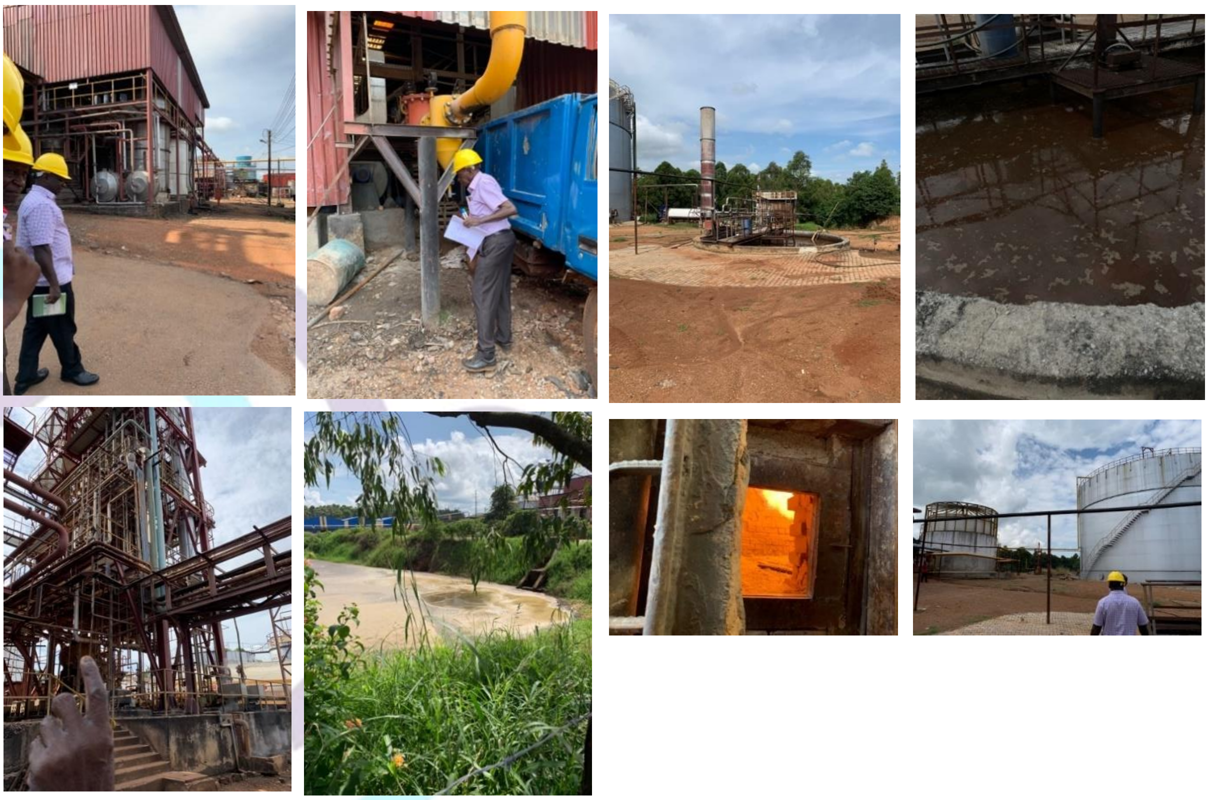

Figure 5.7 Bwendero Dairy Farm (and distillery)

6. Initial techno-economic modelling

6.1 Basis of the analysis

A simple techno-economic analysis has been undertaken for Ghana (Figure 6.1) and Uganda (Figure 6.2), as an initial exploration of the competitiveness of bio-CNG with LPG. An existing spreadsheet model developed for the Engas technology was applied using parameter values chosen to reflect conditions in the two target countries. However, these are only indicative analyses and the assumptions made here must be validated independently.

The analyses make a direct comparison with LPG, based on reported current costs for LPG refill in Ghana and Uganda. The underpinning question is:

- What would be the simple payback period for an investment in a bio-CNG plant, if the resulting bottled gas is sold to households at a price which gives them a cooking cost equivalent to that with LPG?
- Three possible scales of plant are assessed, from a very small plant that could refill only a handful of bottles for household use per day, to a medium scale commercial scale.

Further analyses should also consider bottled bio-CNG as a replacement for traditional wood fuel and charcoal as cooking fuel options, as well as directly calculating the selling price needed for an investable proposition.

The tables below show the assumptions and key stages if the calculation. Notable assumptions are:

- LPG retail prices were assumed to be $1.08/kg in Ghana and $2.6/kg in Uganda. Based on research in other parts of sub-Saharan Africa, that makes for a sensible range of common prices. The only difference in the assumptions in the analysis for Ghana and Uganda was for the LPG prices.
- The Bio-CNG system analysis is designed to fill high pressure cylinders of a similar size to those used for LPG. These would be of a similar filled-weight to LPG, but the energy content would be less than half for an equivalent LPG cylinder. Alternative filling/transport/retail arrangements can be considered but are outside the scope of this initial assessment.
- It is assumed that food waste, or other suitable feedstock is available for free: this reflects the situation that institutions generating such wastes will typically incur costs in disposal or other management, and thus might be willing to provide feedstock at zero cost.
- Similarly, no value for the Bio-CNG system has been included reflecting any 'gate-fees' for taking wastes away. For this first analysis, it is assumed that feedstock reflects neither a cost nor benefit.
- Labour and land costs are included, with the stated assumptions. These are particularly uncertain, as the cases analysed here are hypothetical and not based in any real context. However, these costs are critical in the overall cost-benefit of the system.
- The financial calculations are kept deliberately simple: no discounting is used, and no consideration of how the investment might be financed. The only investment performance measure used is Simple Payback period. Whilst this limits the depth of the analysis, simple payback is widely used as a rule of thumb and screening measure for investments.

A wide variety of feedstocks for AD are available in Ghana and Uganda (as reported in Sections 3 and 4) e.g. sugar mill spent-wash/press-mud, animal manure, cassava starch pulp, vegetable market waste, fish processing waste etc. Some feedstocks are more difficult for direct use in conventional anaerobic digestors, without pre-processing e.g. rice husk, rice straw, cotton seed hull.

In terms of the three different scales of system considered, it is not unreasonable to have a dilemma about whether to go for a large-scale biogas bottling plant or to focus on small scale modular biogas bottling plants. Clearly larger scale systems are going to be more cost effective, while the Capex is still reasonable even in small scale, and energy costs might still be fairly-linear at all scales, but labour costs becomes more sensitive at the small scale. Having said that, if the plant owners are trained to run the plant (which takes about 1-2 hours /day), then small-scale biogas bottling plants may well be considered. Naturally small-scale systems have lesser risk profiles compared to larger scale plants, such as the long-term availability/supply of feedstock, cost of finance, own usage of gas rather than selling to the market etc.

Currently Ghana is not involved in developing any gas purification technologies (although clean-up technologies are employed in independent facilities for their own use, or in trial systems for waste management). Uganda has a small-scale research pilot plant, based on existing gas purification technologies, but is not currently exploring the opportunity further. Large scale biogas plants seem to be more appealing for heating/power projects rather than biogas bottling for cooking initially, which is a market force influencing the decision of a private investor/entrepreneur. Unless there is any surplus biogas, it is apparently more difficult to convince a prospective stakeholder to set up a brand-new large-scale biogas bottling plant dedicated to supply cooking gas to the households, in the absence of a validated business model or the market demand.

The market response to a bottled biogas product could vary depending on the targeted customers and their existing mode of cooking e.g.:

- If they are already using LPG cylinders the driving factor for them would be to save money;
- for those using traditional fuel (firewood, cow dung cake), the driving factor could be the aspiration towards better living-standards, higher productivity, improving health, for which there would be a need for support from respective Governments or e.g. the World Bank to address poverty alleviation, access to clean energy etc.;
- There could be greater uncertainty at this stage, in setting-up a large-scale biogas/bio-CNG bottling plant before validating customers' responses with respect to customer demands in various scenarios e.g.:
    - LPG vs Bio-CNG;
    - Firewood vs Bio-CNG (and other scenarios beyond the scope of this report);
    - Electric cooking vs Bio-CNG cooking;
    - Solar hydrogen cooking vs Bio-CNG for cooking.
- With respect to market risks, it would be pragmatic to start with a smaller/mid-scale AD plant or using the surplus-gas from existing biogas plants to set up biogas purification, bottling and distribution within a catchment area. If the biogas is to be used within the same premises (e.g. institution, hotel etc) then biogas bottling may not be needed, which will save capital and operational cost. Perhaps institutional clients could be the first target customers/market segment to validate the business model for bio-CNG cooking and later on bio-CNG cylinders could be distributed locally to replace LPG cylinders.

6.2 Analysis results for Ghana and Uganda

Figure 6.1 Business Model for Bio-CNG to replace LPG cylinders in Ghana

Engas UK Ltd				
Business Model to produce Bio-CNG to replace LPG cylinders				
Ghana				
Items	**Units**	**Values**	**Values**	**Values**
Plant capacity	**Nm3/h raw biogas output**	**3.00**	**10.00**	**25.00**
LPG Cylinder capacity	kg	14.50	14.50	14.50
LPG price per kg = USD 1.05/kg @ 0.76 £/USD (Ref: Email from Francis)	**£/ cylinder of 14.5kg LPG**	**11.57**	**11.57**	**11.57**
LPG energy density	kWh/kg LPG	13.60	13.60	13.60
LPG Total Energy per bottle	kWh/bottle LPG	197.20	197.20	197.20
LPG price in Ghana on kWh basis	£/kWh LPG	0.06	0.06	0.06
Bio-CNG at 97% CH4 purity	kWh/Nm3 Bio CNG	9.67	9.67	9.67
Bio-CNG density	kg/Nm3 Bio CNG	0.75	0.75	0.75
Bio-CNG energy density	kWh/kg Bio CNG	12.89	12.89	12.89
Keeping the price same on energy content basis for Bio CNG similar to LPG	£/kWh Bio-CNG	0.06	0.06	0.06
Equivalent market price of Bio-CNG on the same energy content basis	**£/kg Bio-CNG**	**0.76**	**0.76**	**0.76**
Cyclinder volume	lt	35.00	35.00	35.00
Bio-CNG Cylinder pressure	bar	248.00	248.00	248.00
Bio-CNG gas volume under pressure	Nm3	8.68	8.68	8.68
Bio-CNG weight under pressure/cylinder	**kg Bio-CNG/cylinder**	**6.51**	**6.51**	**6.51**
Stored Bio-CNG energy	kWh	83.94	83.94	83.94
Equivalent price of each Bio CNG cylinder refill	**£/cylinder CNG**	**4.93**	**4.93**	**4.93**
Required volume of food waste and vegetable market waste@12kg foodwaste/Nm3 raw biogas	**Kg/day foodwaste**	**864.00**	**2,880.00**	**7,200.00**
Cost of feedstock (food-waste) per kg CNG	£/ kg CNG	0.00	0.00	0.00
Cost of feedstock including delivery	**£/day bio waste**	**0.00**	**0.00**	**0.00**
Volume of raw biogas output from digester	Nm3/day raw biogas	72.00	240.00	600.00
Volume of Clean Bio-CNG (57% yield net)	Nm3/day Bio-CNG	41.04	136.80	342.00
Gas Upgrader output capacity	Nm3/h, Clean Bio CNG	1.71	5.70	14.25
Gas Upgrader output capacity	kg/h	1.28	4.28	10.69
Gas Upgrader output capacity	Kg/day	30.78	102.60	256.50
Total CNG production per day	kWh/day	396.86	1,322.86	3,307.14
Number of bio-CNG cylinders produced per day	**cylinders/day**	**4.73**	**15.76**	**39.40**
Income from sales of bio-CNG	**£/day**	**23.29**	**77.62**	**194.05**
Equivalent 14.5 LPG cylinder refills replaced/day	**cylinders/day**	**2.01**	**6.71**	**16.77**
Income/Savings by selling Bio-CNG	**£/day**	**23.29**	**77.62**	**194.05**
Compost (assuming 10% solid content in liquid fertiliser)	**kg/day compost**	**86.40**	**288.00**	**720.00**
Market price of compost (semi dry)	£/kg compost	0.04	0.04	0.04
Income from compost sales	**£/day compost**	**3.46**	**11.52**	**28.80**
Total income per day (Bio-CNG + fertiliser)	£/day	26.74	89.14	222.85
Total income per year (Bio-CNG + fertiliser)	**£ /year**	**8,150**	**27,167**	**67,918**
Capex of AD plant	**£**	**12,000**	**22,000**	**42,000**
Capex of Bio-CNG upgrader and compressor	**£**	**25,000**	**35,000**	**60,000**
Capex of single gas cylinder	£	477	477	477
Capex of gas cylinders for 3days of gas storage	**£**	**6,766**	**22,553**	**56,383**
Total Capex	**£**	**43,766**	**79,553**	**158,383**
Project Manager wage assuming owner- operator at his/her own farm, £600/month	£/year	0	7,200	7,200
Labour cost : £150/month manual labour x 12 months x no of people	£/year	3,600	5,400	7,200
Land lease cost	£/year	0	5,000	10,000
Total labour and land costs	**£/year**	**3,600**	**17,600**	**24,400**
Electricity rate (Ghana)	£/kWh electricity	0.15	0.15	0.15
Energy consumption by biogas upgrader + compressor	kWh/Nm3 raw biogas	0.50	0.50	0.50
Energy consumption by biogas upgrader + compressor	kWh/hour	1.50	5.00	12.50
Cost of electricity to run the bio-CNG + Compressor plant	**£/day**	**5.40**	**18.00**	**45.00**
Servicing and maintenance cost @10% of Capex	**£/year**	**4,377**	**7,955**	**15,838**
Total overhead & operating cost	**£/ year**	**7,982**	**17,618**	**24,445**
Net operating Profit	**£/year**	**168**	**9,549**	**43,473**
Simple Payback period	**years**	**260.26**	**8.33**	**3.64**

Figure 6.2 Business Model for Bio-CNG to replace LPG cylinders in Uganda

Engas UK Ltd Business Model to produce Bio-CNG to replace LPG cylinders				
Uganda				
Items	**Units**	**Values**	**Values**	**Values**
Plant capacity	**Nm3/h raw biogas output**	**3.00**	**10.00**	**25.00**
LPG Cylinder capacity	kg	14.50	14.50	14.50
LPG refill price per kg = USD 2.6/kg @ 0.76 £/USD (Ref: Email from Edson)	**£/cylinder of 14.5kg LPG**	**28.65**	**28.65**	**28.65**
LPG energy density	kWh/kg LPG	13.60	13.60	13.60
LPG Total Energy per bottle	kWh/bottle LPG	197.20	197.20	197.20
LPG price in Uganda on kWh basis	£/kWh LPG	0.15	0.15	0.15
Bio-CNG at 97% CH4 purity	kWh/Nm3 Bio CNG	9.67	9.67	9.67
Bio-CNG density	kg/Nm3 Bio CNG	0.75	0.75	0.75
Bio-CNG energy density	kWh/kg Bio CNG	12.89	12.89	12.89
Keeping the price same on energy content basis for Bio CNG similar to LPG	£/kWh Bio-CNG	0.15	0.15	0.15
Equivalent market price of Bio-CNG on the same energy content basis	**£/kg Bio-CNG**	**1.87**	**1.87**	**1.87**
Cyclinder volume	lt	35.00	35.00	35.00
Bio-CNG Cylinder pressure	bar	248.00	248.00	248.00
Bio-CNG gas volume under pressure	Nm3	8.68	8.68	8.68
Bio-CNG weight under pressure/cylinder	**kg Bio-CNG/cylinder**	**6.51**	**6.51**	**6.51**
Stored Bio-CNG energy	kWh	83.94	83.94	83.94
Equivalent price of each Bio CNG cylinder refill	**£/cylinder CNG**	**12.20**	**12.20**	**12.20**
Required volume of food waste and vegetable market waste@12kg foodwaste/Nm3 raw biogas	**Kg/day foodwaste**	**864.00**	**2,880.00**	**7,200.00**
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Cost of feedstock including delivery	**£/day bio waste**	**0.00**	**0.00**	**0.00**
Volume of raw biogas output from digester	Nm3/day raw biogas	72.00	240.00	600.00
Volume of Clean Bio-CNG (57% yield net)	Nm3/day Bio-CNG	41.04	136.80	342.00
Gas Upgrader output capacity	Nm3/h, Clean Bio CNG	1.71	5.70	14.25
Gas Upgrader output capacity	kg/h	1.28	4.28	10.69
Gas Upgrader output capacity	Kg/day	30.78	102.60	256.50
Total CNG production per day	kWh/day	396.86	1,322.86	3,307.14
Number of bio-CNG cylinders produced per day	**cylinders/day**	**4.73**	**15.76**	**39.40**
Income from sales of bio-CNG	**£/day**	**57.66**	**192.20**	**480.51**
Equivalent 14.5 LPG cylinder refills replaced/day	**cylinders/day**	**2.01**	**6.71**	**16.77**
Income/Savings by selling Bio-CNG	**£/day**	**57.66**	**192.20**	**480.51**
Compost (assuming 10% solid content in liquid fertiliser)	**kg/day compost**	**86.40**	**288.00**	**720.00**
Market price of compost (semi dry)	£/kg compost	0.04	0.04	0.04
Income from compost sales	**£/day compost**	**3.46**	**11.52**	**28.80**
Total income per day (Bio-CNG + fertiliser)	£/day	61.12	203.72	509.31
Total income per year (Bio-CNG + fertiliser)	**£ /year**	**20,181**	**67,271**	**168,178**
Capex of AD plant	**£**	**12,000**	**22,000**	**42,000**
Capex of Bio-CNG upgrader and compressor	**£**	**25,000**	**35,000**	**60,000**
Capex of single gas cylinder	£	477	477	477
Capex of gas cylinders for 3days of gas storage	**£**	**6,766**	**22,553**	**56,383**
Total Capex	**£**	**43,766**	**79,553**	**158,383**
Project Manager wage assuming owner- operator at his/her own farm, £600/month	£/year	0	7,200	7,200
Labour cost : £150/month manual labour x 12 months x no of people	£/year	3,600	5,400	7,200
Land lease cost	£/year	0	5,000	10,000
Total labour and land costs	**£/year**	**3,600**	**17,600**	**24,400**
Electricity rate (Uganda)	£/kWh electricity	0.15	0.15	0.15
Energy consumption by biogas upgrader + compressor	kWh/Nm3 raw biogas	0.50	0.50	0.50
Energy consumption by biogas upgrader + compressor	kWh/hour	1.50	5.00	12.50
Cost of electricity to run the bio-CNG + Compressor plant	**£/day**	**5.40**	**18.00**	**45.00**
Servicing and maintenance cost @10% of Capex	**£/year**	**4,377**	**7,955**	**15,838**
Total overhead & operating cost	**£/ year**	**7,982**	**17,618**	**24,445**
Net operating Profit	**£/year**	**12,199**	**49,653**	**143,733**
Simple Payback period	**years**	**3.59**	**1.60**	**1.10**

6.3 Discussion of modelling results

Given that the only difference in the assumptions in the analysis for Ghana and Uganda was for the retail price for LPG, assumed to be $1.08/kg in Ghana and $2.6/kg in Uganda, comparison of the payback results shows how sensitive they are to fuel selling price. For Uganda, all three system sizes achieve payback times below 4 years, and for the two larger systems the payback is within the range of one to two years. However, for Ghana, only the largest system achieves less than 4 years, and the smallest system won't payback at all.

There is considerable uncertainty over the appropriate parameter values throughout the analysis. However, a general conclusion is that where competing fuel prices are relatively high, a Bio-CNG system at even small to medium scale could be a viable proposition.

Engas UK, and others, have previously demonstrated the technical feasibility of linking biogas upgrade and compression technologies to AD at small scales, with packaged systems and tight integration of material and energy flows. The fieldwork and in-country studies within this project have demonstrated ready sources of biogas from existing AD facilities, and multiple feedstocks from a variety of other sectors. The initial financial analysis here suggests that the conditions in sub Saharan Africa can offer practical opportunities to implement Bio-CNG for cooking.

As mentioned above, there are numerous questions to be explored further to tighten up the choice of scenarios and parameter values for this financial analysis. However, there are also a wider range of questions surrounding the practicalities of implementing bio-based energy systems, and of user interest. These issues were a key focus of the workshop and conference discussed in the following section.

7. Workshop and Conference

A workshop was held at the University of Surrey on 15th and 16th October 2019. Project partners from Ghana and Uganda attended along with invited experts from the respective countries. The Workshop programme and attendees are given in Appendix 5.

The subject of biogas as a clean cooking option was opened to a wider audience at a 2-day conference on 17th and 18th October, at the University of Surrey. Invited delegates were from respective Ministries and Associations from the project partner countries, as well as additional delegates from India, the USA and UK. The conference was co-hosted by the UK MECS project and representatives from this initiative were also invited. The conference programme is given in Appendix 6.

7.1 Outcomes of the Workshop of project partners

The findings of the studies undertaken for Ghana and Uganda were presented at a 2-day workshop, held at the University of Surrey. The workshop was attended by the research team members at each institution, plus a small number of additional commercial and policy experts from Ghana and Uganda; the workshop was joined on day 2 by a small number of further experts from Nigeria and the UK.

Discussions were held around the specific country scoping studies, to understand the current status of AD and biogas in the countries, and the views of stakeholders towards the bottling concept.

In both Ghana and Uganda, there is strong policy support for renewables generally, and for bioenergy within that. Agri-industry residues are seen as a 'free' resource and the impacts of unmanaged disposal are well recognised. Policy-makers are also active in both countries in seeking to advance clean cooking. In Ghana the priority has been towards LPG; despite high electricity access rates (of some 85%) prices are very high. In Uganda a variety o clean cooking options are being pursued, including a programme to roll out household-scale biogas digestors.

As mentioned in section 5.2.2, Uganda does also have one existing pilot of biogas upgrading and bottling, undertaken by the National Livestock Resource Research Institute and the National Biogas Alliance, and funded by the World Bank. Unfortunately, the key person responsible for this plant was unable to travel to join the workshop. However, the pilot is evidence of a nascent commercial interest in bottling biogas in Uganda, although this has not yet gained significant traction.

Experience was also shared of attempts to implement bottled biogas at Ajima Farms in Nigeria. At a large poultry farm, the management have invested in AD and electricity generation from biogas. Given lack of availability of other clean cooking options in surrounding communities, they sought to establish a biogas bottling plant, using engineering expertise from neighbouring Benin Republic. A feasibility study showed that the costs of the fuel would be too high for local households to afford, and the project did not proceed. The key barrier was that most local households are able to gather firewood for free, and thus paying for cooking fuel would be an additional burden. Ajima Farms considered more distant markets, where cooking fuels are paid for. However, the nearest town is currently already using LPG and it was felt there would be little interest in a biogas alternative.

The workshop explored the range of issues and challenges facing further development of bottled biogas. At a high level, these were summarised as:

1. Biogas quality and AD feedstock:
- Uncertainties about impact of gas quality on indoor air quality and health
- Feedstock for AD affects gas quality, and/or affects complexity and cost of clean-up needed

2. User experience:
   - Need acceptable/attractive/reliable user experience for cooking (eg flowrate, cooking power)
   - Need acceptable/attractive user experience for gas supply (eg weight of bottles; frequency of refilling, cost)
3. Biogas applications:
   - Competing uses for the biomass? (including returning biomass directly to land to maintain soil fertility, or for onsite power generation)
   - Competing uses for biogas, or opportunities for multi-use (eg cooking, vehicle fuels, electricity)
4. Overall 'system' performance:
   - Is the overall environmental performance (eg per meal cooked) better than for competing fuel options?
   - How to combine the dual benefits of 'waste management' with access to clean cooking?
   - How to decide the optimum 'scale' of system (AD to clean-up to bottling), trading off costs and benefits from simple small scale to more efficient but complex larger scale?
   - Need to account for indigenous capacity for equipment manufacture or assembly; real system costs for local implementation; maintainability and reliability
   - How to evaluate alternative biogas applications etc?

Day 1 concluded with exploration of the range of potential funding sources for further research and/or demonstration activities for biogas bottling. This included:

1. UKRI, Innovate UK:
   - Agri-tech catalyst round 9: agriculture and food systems innovation. Competition closes: Wednesday 8 January 2020. https://apply-for-innovation-funding.service.gov.uk/competition/447/overview
   - Energy catalyst round 8. Expected early in 2020. Round 7 details : https://apply-for-innovation-funding.service.gov.uk/competition/373/overview
2. GCRF
   - Demonstrate impact in meeting the sustainable development goals: phase 1. Demonstrate market-creating innovations in lower income countries and emerging economies. Competition closes: Wednesday 13 November 2019. https://apply-for-innovation-funding.service.gov.uk/competition/443/overview
   - Some other open calls, but currently limited. https://www.ukri.org/research/global-challenges-research-fund/
3. Modern Energy Cooking Services programme, challenge funds. Next round expected Spring 2020. https://www.mecs.org.uk/challenge/
4. Department for International Development, International development funding
   - Call database available at https://www.gov.uk/international-development-funding
5. Newton Fund. Targeted calls throughout the year – nothing correctly open which would be applicable to Africa. https://www.newtonfund.ac.uk/
6. Ayrton Fund. Development and testing of new technology targeted at tackling climate change in developing countries. Initial announcement of intention to made start a new £1billion fund, but no programme details

yet. https://www.gov.uk/government/news/british-scientists-to-help-tackle-climate-change-through-new-1-billion-fund

7. Protection and restoration of forests. Initial announcement of further funding allocations made but no programme details yet. https://www.gov.uk/government/news/prime-minister-announces-ambitious-package-of-support-to-protect-and-restore-the-worlds-forests

Of these, the UKRI Agri-tech Catalyst round 9 is potentially highly relevant for biogas bottling being considered at agri-business or farm level, where this could add an additional revenue stream and enhance the business' viability. The GCRF demonstration call is also highly relevant for piloting, however the deadline for proposals is very tight. For most of these funding routes it would be essential to have close engagement (even leadership) from commercial organisations, either in the UK or in Africa. In some cases, significant matched funding is also required from the commercial partners.

On day 2, the participants separated into 2 breakout groups, each tasked with scoping out the activities needed to address the identified challenges. One group focused on a whole systems approach to characterise the costs and benefits of the bottling biogas concept as a whole including for poor community customer segment, and the other focused on bottom-up, site specific pilot study approaches. Both groups highlighted similar issues which were articulated in different ways, according to the experiences of the people in each group.

The Systems group mapped out the physical/technical system stages associated with bottling biogas for household use, and then identified the wide set of associated methods or types of analysis that would be needed to characterise the overall costs and benefits (or impacts). They also considered the different questions or applications that such an overall systems analysis could be used to address, including the relative merits of different system scales and the overall business case and its appeal to potential investors.

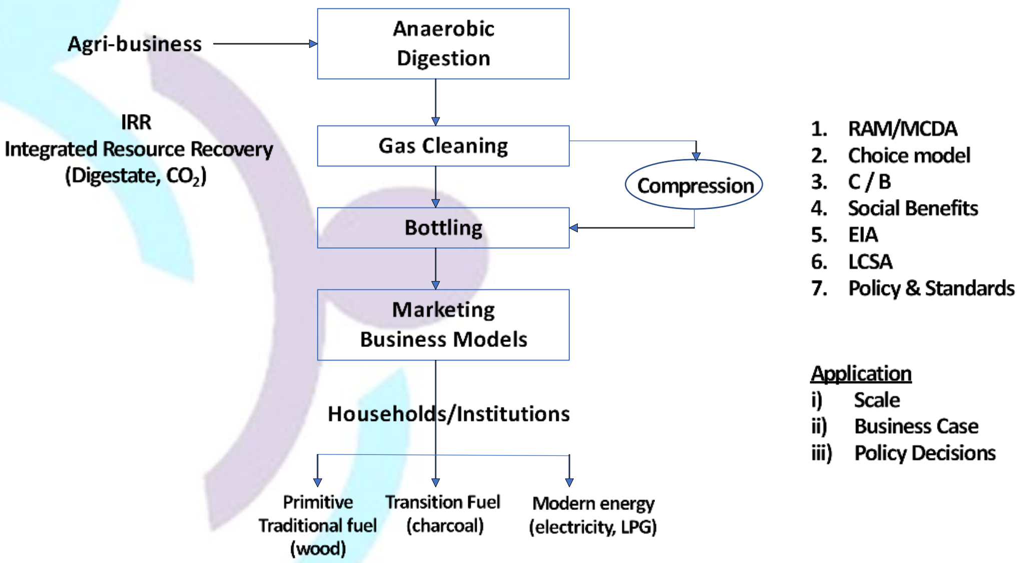

Figure 7.1. Outcomes from 'Systems Study' break-out group

The piloting group explored the requirements for pilot or demonstration projects intended to look at the opportunity for bottling. Conclusions were:

- Pilot studies should be centred on the identification of suitable opportunities where biogas is currently produced in excess or where current systems are not optimized for biogas production.
- Important to recognise country specific variances, including in policy support mechanisms
- The current project effectively includes scoping studies, including discussions and site visits to agri- and waste- businesses who could be appropriate hosts for pilot activities. These initial studies have brought project partners to this workshop stage
- However, further pre-pilot studies (including modelling) will be needed as part of any piloting proposal, to define:
  - scale of operation
  - other uses of biogas
  - maximize value of co-products (effluent/CO_2/solids/fertilisers)
  - business models (entrepreneurial opportunities)
  - centralized or decentralized systems
  - understanding market demand
  - household needs/preferences/affordability
  - H&S, environmental and technical standards including management and distribution of compressed gas systems and waste handling
  - EIS template (country specific)
  - gender impact assessment/analysis

7.2 Outcomes of the Conference

Following the workshop, an additional 20 experts from East and West Africa, India, the USA, and the UK joined the group for a 2 day conference on the wider possibilities for containerized bio-derived gases for clean cooking, in particular brining in the alternative option of bio-LPG. The programme comprised the following. (The presentation materials are available at https://tinyurl.com/y4ccrczx)

Session 1: Biogas Overview – Ghana, India and Uganda

- Joshua Bright Amenorfe, Biogas Association of Ghana, Overview of biogas developments and industry in Ghana
- Atma Ram Shukla, Indian Biogas Association, Overview of biogas developments and the industry in India
- Edson Twinomujuni, UCPC, Uganda, Overview of biogas developments and the industry in Uganda

Session 2: Routes for biomass to gas for clean cooking

- Amit Roy, Engas and Portsmouth University, Innovation in small scale production and compression technology
- Kimball Chen, GLPGP, Bio-LPG: technologies and prospects

Session 3: Bio-CNG opportunities in Africa: Ghana and Uganda case studies

- Francis Kemausuor, KNUST, Ghana: current activities, commercial interest
- Edson Twinomujuni, UCPC, Uganda: current activities, commercial interest

- Amit Roy, Engas and Portsmouth University, Business model analysis for Bio-CNG: initial results

Session 4: Bio-gas cooking experience in other parts of Africa and Asia

- Fatima Oyiza-Ademoh, Ajima Farms, Off-grid energy project, Nigeria
- Zacchariah Ross, BBOXX Cook, Biogas in Rwanda: opportunities and challenges
- Joel Chaney & Charlotte Ray, CREATIVenergie, Exploring the feasibility of portable biogas in Tanzania

Session 5: Opportunities and challenges: Biogas production/AD

- Michael Chesshire, REA/Lutra, UK experience in the development of AD operations and biogas markets – opportunities and challenges
- Jon Cloke, MECS and LCEDN, Biogas in Bangladesh
- Rokiah Yaman, LEAP Micro AD, Micro AD: advantages and challenges of decentralised biogas production

Session 6: Key barriers/issues in implementation

- Sarah Hunter, UCL, Feedstocks, scales & products
- Paula Edze, Coordinator, Sustainable Energy for All Secretariat, Ghana
- Elisa Puzzolo, GLPGP, Bio-LPG: regulations and safety

Thomas Minter, World Biogas Association and Malaby Biogas Ltd, The Global Potential of Biogas. Insights into scale and delivery and applications (30 mins)

Roundtable discussions: what are the top 3 actions needed to bring forward options for containerised biogas?

Session 7: Policy and investment support

- Mr. Julius Nkansah-Nyarko, Energy Commission Ghana, Technical regulation and policy formulation
- Ms. Justine Akum, Ministry of Energy and Mineral Development Uganda, Policy approach Uganda

Following a series of presentations on the potential for AD technology, as developed in different countries, deeper assessment of technologies for AD, clean-up and bottling and exploration of the challenges that will need to be overcome, conference delegates were asked to work in groups to identify the 3 key issues and research priorities they anticipated in developing bottled biogas as a clean cooking opportunity. The outcomes are presented in Table 7.1.

Table 7.1. Priorities for developing bottled biogas

Group 1	
1	Cost Benefit Analysis – direct and indirect cost and benefits to understand the potential of established AD facilities to establish how biogas could be utilized.
2	Rural setting – what data needs to be collected to really understand the local situation and what is required to implement biogas bottling systems
3	Cooking fuel preferences
4	Modelling tool to be able to establish if a project could be viable in quick and easy way
Group 2	
1	Feasibility study cost-benefit; social sustainability at the country level down to regional level
2	Waste assessment – what is the real potential at the country level
3	H&S – what kind of equipment and infrastructure would be required e.g. types of cylinders (cost effective; re-usable; safe)
Group 3	
1	Evidence based demonstration - cataloguing business models and looking at failed models

2	Use perception – preliminary studies around
3	Adoption of LPG – how to convince or advocate for bottled Bio-CNG when direction seems to be in promoting/developing LPG
4	How to sell idea to commercial parties
5	Environmental regulation assessment – policy and avocation
Group 4	
1	Security of feedstock
2	Understanding the geospatial level where feedstock arises to inform location of AD facilities
3	Pricing and distribution so that technology can work for the 'daily economy' – on a meal to meal basis – also to influence daily behaviours and potentially reduce household cooking cost
4	Education and behaviour – understanding the priorities of the household and then to understand teaching and educational requirements
5	Cost of compression and can it work when pressure is so high and potentially dangerous

The conference concluded with a general discussion of the next steps for the project and the wider group. Key actions include:

- Conference presentations to be shared with all participants
- Finalisation of the project report
- Blog and social media activity to raise the profile of containerised biogas
- Further exploration of possible funding routes
- Development of proposals for further research, specific feasibility studies and piloting activities
- Potentially establishing a forum or partnership of interested organisations and individuals to progress this area

8. CONCLUSIONS

8.1 Context and study aims

Almost 3 billion people use biomass, coal or dung for cooking: smoke from fuel combustion contributes to some 4 million premature deaths annually. The United Nations Framework Convention on Climate Change (UNFCCC) Sustainable Development Goals (SDGs) commit countries to improving access to clean energy, but progress is slow. Furthermore, achieving access for poorer people often involves provision of low-power electricity connections, not addressing cooking.

Clean cooking initiatives include efficient solid-fuel stoves, various forms of household-scale waste digestors for biogas, innovations for electricity using batteries and use of bottled gas (notably Liquefied Petroleum Gas (LPG)), all of which have different greenhouse-gas (GHG) emission impacts.

In this scoping study, conducted by partners in the UK, Ghana and Uganda, a different approach was: biogas derived from AD being stored in pressurised containers, similar to those used for LPG, allowing distribution to households. Such approaches are already being implemented in parts of India but have had little consideration in Sub-Saharan Africa. *The project sought to understand the opportunities for bottled biogas for cooking in Africa, why it has not already taken off, and the key issues to be addressed to enable this.* Innovation in AD technology, cleaning and upgrading of biogas to allow compression and bottling and development of distribution systems may all be needed, with new business models and supportive policy.

The scoping study was conducted from February 2019 onwards and comprised:

- International literature and market review of the AD industry and technology options for biogas cleaning, upgrading and compression, to provide context for country-specific research
- Review of current biogas activity in Ghana and Uganda
- Development of a database of relevant stakeholders in Ghana and Uganda
- Visits and meetings with organisations, academics and potential commercial partners in UK, Ghana and Uganda; attendance at UK AD & World Biogas Expo 2019
- Review of relevant standards, regulations and policies in Ghana and Uganda
- Initial scoping of promising applications for bottling biogas
- Undertaking initial system modelling for biogas cleaning, compression and bottling scenarios at a variety of scales for Ghana and Uganda, based on Engas UK's technology

The scoping study has resulted in this literature and technology review, with input from the Ghana and Ugandan partners and the technology partner Engas UK, and initial techno-economic modelling of scenarios relevant for Uganda and Ghana. This report has been finalised with input from the Workshop and Conference held at the University of Surrey, 15th-18th October 2019. The report will be made available as a CES working paper and a MECS working paper in early 2020.

8.2 Summary of study findings

The study has introduced a new area of technology for AD/biogas developments in both countries and has identified key organisations for future collaborations, notably for feasibility studies and/or piloting, with academic, consultancies and commercial partners. For example, in Ghana, a commercial partner (a chicken slaughterhouse) has been identified which currently uses AD to treat effluent and waste from processing facilities - trialling of a biogas clean-up and bottling facility would provide a clean cooking fuel for the rural community surrounding the facility, including a secondary school; in Uganda, 1 partner with significant capacity for biogas production which is currently not optimised, would provide an opportunity for optimising an AD and biogas clean-up and bottling facility, providing a clean cooking option as a commercial opportunity.

Some high-level findings include:

AD is a process which facilitates the breakdown of organic matter, in the absence of oxygen. Naturally occurring, it results in the production of methane (CH_4), carbon dioxide (CO_2), water (H_2O) and other gases, in oxygen depleted environments such as water-logged soils, effluent ponds and land fill. In recent years, the AD process has gained significant interest as a technological solution to the management of waste, in the provision of energy and as an opportunity for addressing greenhouse gas (GHG) emissions which contribute to climate change.

Residues and waste effluent streams from agro-industry processes are of concern in both Uganda and Ghana, with policy-makers seeking ways to stimulate better controlled management, either through regulation or incentives. In conjunction with sections of the industry, there is considerable technical and system innovation taking place, eg towards greater resource integration, consistent with circular economy principles. AD can be an important part of that approach, and as such, the prospects are for growing interest and application of AD and further attention to biogas uses.

In many regions of the world, AD technologies have been promoted and adopted at a variety of scales, to provide energy for heat and power in household and commercial applications. These range from small-scale household and community digestors providing raw biogas for heating, cooking and lighting, to larger scale commercial applications providing heat and power to processing facilities and for wider distribution to communities, (requiring cleaning and upgrading of biogas to biomethane, which can then be used directly as a replacement for natural gas in gas grids or in the provision of electricity after conversion of the gas to electrical power).

Generally the science behind the process of AD is well known and the commercialization of AD technologies has led to a proliferation of studies and applications to better understand the organic matter feedstocks for the process, to optimize AD systems and to target the end use biogas or upgraded biomethane. Many of these technologies are sophisticated and costly, requiring high capital costs and on-going operation and maintenance by trained personnel, and hence are best suited to relatively large commercial scales. In considering bottled biogas opportunities in Africa, particularly in rural settings, the study explored options which may be more cost effective and practical in these circumstances.

Identifying feedstock resources, appropriate AD system designs for the scale and location of potential pilot sites and understanding local markets for distribution and sale of bottled biogas product are all aspects which need to be considered and further assessment of local conditions will be required. Promising options were found to include the treatment of waste from livestock facilities in Ghana and the treatment of effluent waste from alcohol production facilities in Uganda.

Smaller scale and inherently lower cost gas clean-up and compression technologies are becoming available. Some experience with these in India and in the UK was presented at the conference, and a pilot plant has been established in Uganda. One novel technology developed by Engas UK, a partner in this study, was evaluated and initial techno-economic modelling was undertaken for application in Uganda or Ghana, presented in section 6.

Figure 8.1 AD systems and the proposed opportunity for compressed and bottled biogas
Modified from World Biogas Association (2014)

The modelling demonstrated the potential viability of small-scale Bio-CNG plants, driven by low capital cost of the Bio CNG upgrader and compressor. Simplified payback analysis indicates there is a viable investment proposition, worthy of more detailed investigation, using data for real cases. While the analysis so far has not considered many of the challenging issues, the headroom in the payback times suggests scope to tackle issues such as:

- discounted pricing for Bio-CNG to introduce it to the market as a replacement for LPG.
- paying for feedstock if necessary
- marketing budget to overcome lack of awareness of Bio-CNG

Overall, this scoping study concludes that:

- There is an ongoing need for clean cooking options in Ghana and Uganda
- Biogas from AD offers a relatively inexpensive route to low carbon energy, especially when its benefits for management of agro-industry residues or other organic waste streams is considered
- Biogas can be a valuable fuel for own-use by industries or waste operators, but surpluses are common, or feasible given potential feedstock availability
- Low cost technologies for appropriate levels of gas upgrading, and compression and bottling, are at pre-commercial demonstration and pilot implementation phase
- Initial analysis suggests that such systems could be implemented to derive cooking fuels that would compete favourably in price with other commercial fuels, including LPG

The question then remains: given the above, why are we not seeing widespread interest in bottled biogas in Africa?

The answer comprises a series of issues and barriers, at least including.

- Different approaches being taken to manage residues and biomass feedstocks, competing uses for bioresources and biogas, and varying enforcement of regulations, which has limited the drive for more sustainable management
- Uncertainties about the likely user experience for bottled biogas, with questions remaining about likely price and frequency of bottle refilling required, as well as cooking preferences and requirements
- The benefits of managing residues and effluent using AD systems are split between the provision of clean energy (including the clean cooking sector), requirements of the agro-industry (including maintenance of land productivity and internal energy requirements) and waste management sectors
- Uncertainties about appropriate scale of a system, from micro-scale close to users up to large industrial scale, with region bottle distribution
- Lack of in-country technical expertise (in some places), or lack of experience with these technologies

The scoping study has brought clarity to the nature of the barriers and has helped identify key players and existing sources of information in each area. The next step is proposed to be pilot activities in one or both of Uganda and Ghana, to demonstrate low cost gas clean-up and compression technology, linked to sources of AD biogas, and in parallel to undertake research into household cooking needs and fuel preferences. The overall aim is to develop one or more investable propositions.

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Appendix 1. Improved and Clean Cooking Stoves – design and classifications

	"Improved" solutions		"Clean" solutions		
	Legacy and basic ICS	**Intermediate ICS**	**Advanced ICS**	**Modern fuel**	**Renewable fuel**
Key features	Small functional improvements in fuel efficiency over baseline technologies; typically artisanally produced	Rocket-style designs with focus on highly improved fuel efficiency; includes both portable and built-in models	Fan or natural-draft gasifiers with high fuel and combustion efficiency; often designed for pellet/ briquette fuels	Stoves that rely on fossil fuels or electricity; have high fuel efficiency and low emissions	Derive energy from renewable non-woodfuel energy; often used as supplementary stoves
Technologies	• Legacy biomass and coal chimney stoves[1] • Basic efficient charcoal • Basic efficient wood	• Portable rocket stoves • Fixed rocket chimney • Highly improved (low CO_2) charcoal stoves	• Natural-draft gasifier (top-loading updraft (TLUD) or side-loading) • Fan gasifier/fan jet • Combination TLUD and charcoal stoves	• LPG • Electric (including induction) • Natural gas stoves • Kerosene stoves[2]	• Biogas • Ethanol • Solar • Retained heat cookers
Efficiency	Tier 0–2	Tier 2–3	Tier 3–4	Tier 4	Tier 3–4
Emissions[3]	Tier 0–1	Tier 1–2	Tier 2–3	Tier 3–4	Tier 3–4
Overall benefits	Moderate				High

[1] Legacy stoves categorized as improved within typology but actual performance of many legacy stoves likely falls below provisional ISO/IWA standards
[2] Controlled tests of good quality kerosene pressure stoves show low emissions, but field data suggests that many kerosene stoves are actually highly polluting
[3] Particulate matter ($PM_{2.5}$) emissions at point of consumption; research suggests that high rating (Tier 3+) needed for significant health positive impacts

Figure A1.1 Classification of stove types
Source: The World Bank (2014)

Appendix 2. AD designs for small-scale applications

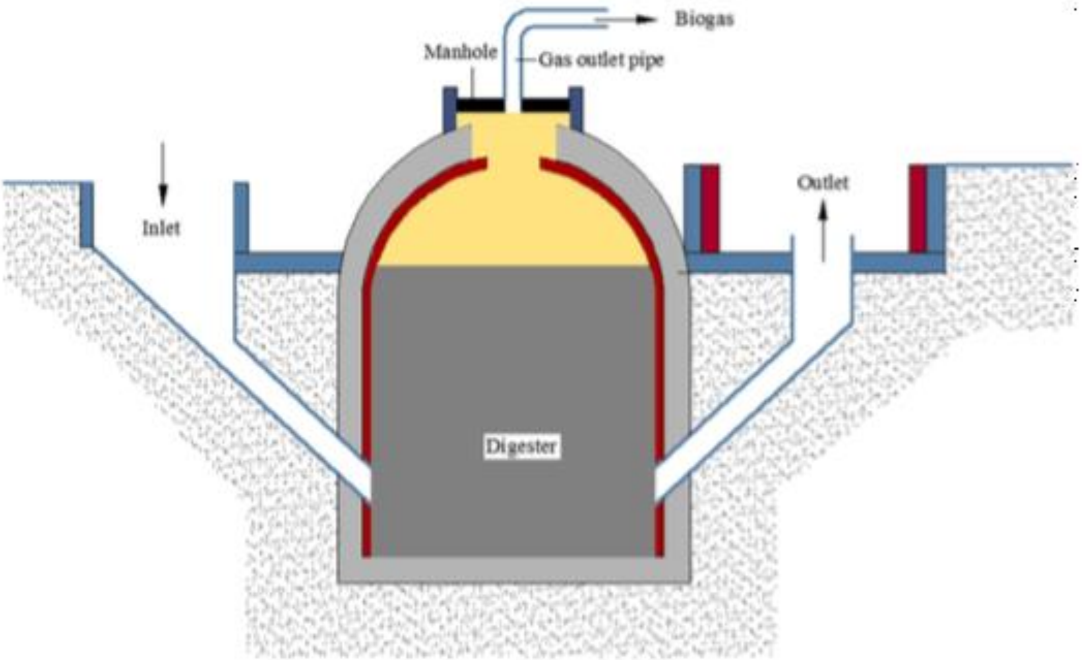

Figure A2.1 Fixed dome (Chinese type) digestor
Source: Morgan et al. (2018), adapted from Gunnerson et al. (1986)

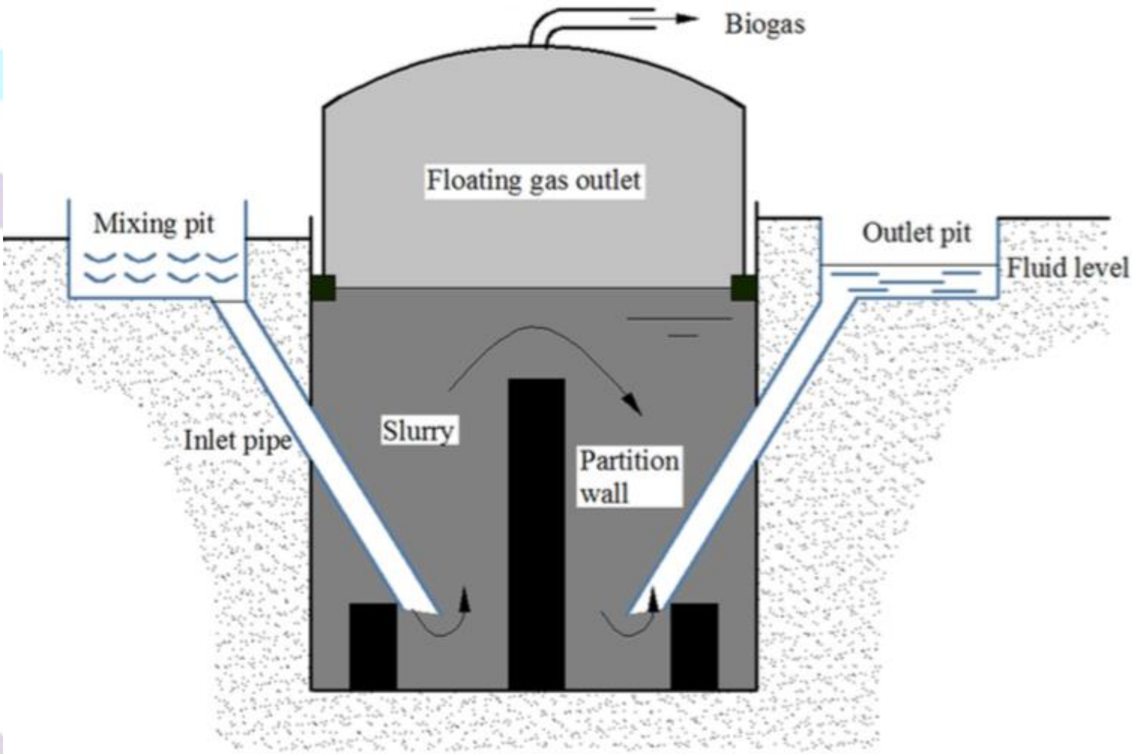

Figure A2.2 Floating cover (Indian type) digestor
Source: Morgan et al. (2018), adapted from Gunnerson et al. (1986)

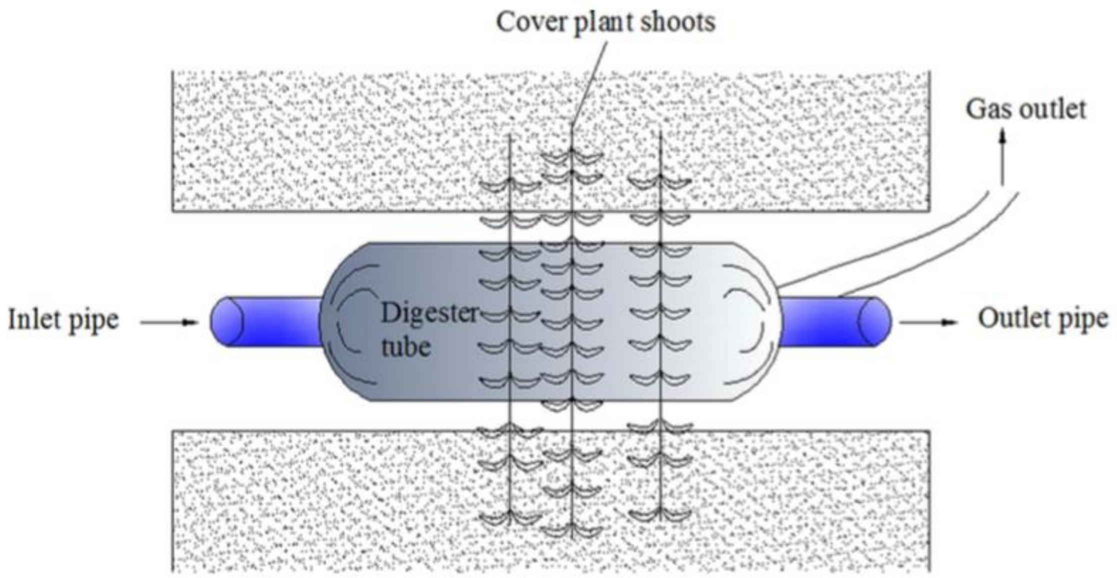

Figure A2.3 Polyethylene tubular digestor
Source: Morgan et al. (2018), adapted from Plochl and Heiermann (2006)

Table A2.1 Factor comparisons for small-scale AD designs

Factors	Fixed dome	**Floating drum**	**Tubular design**	**Plastic containers**
Gas storage	Internal Gas storage up to 20 m³ (large)	Internal Gas storage drum size (small)	Internal eventually external plastic bags	Internal Gas storage drum sizes (small)
Gas pressure	Between 60 and 120 mbar	Upto 20 mbar	Low, around 2 mbar	Low around 2mbar
Skills of contractor	High; masonry, plumbing	High; masonry, plumbing, welding	Medium; plumbing	Low; plumbing
Availability of Material	yes	yes	yes	yes
Durability	Very high >20 years	High; drum is weakness	Medium; Depending on chosen liner	Medium
Agitation	Self agitated by Biogas pressure	Manual steering	Not possible; plug flow type	Evtl Manual steering
Sizing	6 to 124 m³ digestor vol	Up to 20 m³	Combination possible	Up to 6 m³ digestor vol
Methane emission	High	Medium	Low	Medium

Appendix 3. Energy and Financial costs comparisons for biogas upgrading technologies

Table A3.1 Energy Consumption of biogas upgrading technologies
Source: Sun et al. (2015)

	Refs.	Energy consumption (electricity)	Efficiency (%)	Range of efficiency (%)	Median (%)	Source
Water scrubbing	[12]	0.45–0.90 kW h/N m^3 cleaned gas	88.9–92.8	88.9–92.8	90.9	Plant and supplier
Water scrubbing + regeneration	[12]	0.45 kW h/N m^3 cleaned gas	92.8	92.7–96.0	94.4	Plant and supplier
	[24]	770 MJ/ton CO_2	95.1			Personal communication
	[25]	0.2–0.32 kW h/N m^3 raw gas	93.9–95.7			Calculation and supplier
	[17]	0.46 kW h/N m^3 cleaned gas	92.7			Plant + literature
	[16]	0.25–0.3 kW h/N m^3 raw gas; 0.3–0.5 cleaned gas	93.7–95.6			Company
	[55]	0.23 kW h/N m^3 raw gas;	96.0			
Cryogenic separation	[24]	1275 MJ/ton CO_2	93.1	84.9–96.7	90.8	Cal
	[16]	0.2–0.28 kW h/N m^3 raw gas	95.5–96.7			Cal
	[30]	0.8–1.54 kW h/N m^3 cleaned gas	86.4–92.5			Cal
	[46]	0.45–1.05 kW h/N m^3 raw gas	84.9–92.9			Cal
	[55]	0.35 kW h/N m^3 raw gas;	93.0			
Physical absorption	[24]	1069 MJ/ton CO_2	91.0	90.0–95.5	92.8	–
	[16]	0.2–0.3 kW h/N m^3 and 0.2 kW h/N m^3 (heat) raw gas	94.6–95.5*			Plant
	[17]	0.49–0.67 kW h/N m^3 cleaned gas	90.0–91.5			Plant + literature
Chemical absorption	[12]	0.3 kW h/N m^3 cleaned gas	88.5	88.5–97.7	93.1	Plant
	[24]	433 MJ/ton CO_2	97.6			–
	[16]	0.1–0.15 kW h/N m^3 and 0.5–0.75 kW h/N m^3 (heat) raw gas	96.7–97.7*			Supplier
	[32]	0.058 MJ/N m^3 and 5.89 MJ/N m^3 (heat) cleaned gas	91.7*			Cal
	[6]	0.12 kW h/N m^3 and 0.44 kW h/N m^3 (heat) cleaned gas	97.7*			–
	[17]	Electricity 0.27 kW h/N m^3 cleaned gas	97.3			Plant + literature
	[55]	Electricity 0.5 kW h/N m^3 raw gas + heat 0.5–1 kW h/N m^3	93–96			
Pressure swing absorption	[24]	915 MJ/ton CO_2	92.1	84.8–93.6	89.2	–
	[12]	0.3–1.0 kW h/N m^3 cleaned gas	84.8–90.4			Plant
	[16]	0.23 kW h/N m^3 raw gas	93.2			Company
	[17]	0.46 kW h/N m^3 cleaned gas	93.6			Plant + literature
	[31]	< 0.3 kW h/N m^3 raw gas	91.8			–
	[55]	0.25 kW h/N m^3 raw gas	93			
Membrane technology	[24]	1264 MJ/ton CO_2	82.4	82.4–98.0	90.2	–
	[40]	0.15–0.22 kW h/N m^3 raw gas	88.8–89.8			Sim
	[16]	0.18 kW h/N m^3 raw gas	95			Company
	[17]	0.25–0.43 kW h/N m^3 cleaned gas	86.5–87.9			Plant + literature
	[55]	0.21 kW h/N m^3 raw gas	98			
In-situ upgrading	NA					
Hydrate formation	NA					
Biological methods	NA					

* Assumption: 1 kW h electricity equivalent to 4 kW h heat.

Table A3.2 Capital & operating and maintenance costs of upgrading technologies
Source: Sun et al. (2015)

	Refs.	CAPX	O&M	CAPX EUR/kW h	O&M Euro cent/ kW h	Source
Water scrubbing	[11]	660 m^3/h: 2.5 mEUR	–	660 m^3/h: 644	–	Plant data
	[12]	250 m^3/h: 0.9–1.1 mEUR*	–	250 m^3/h: 585–731	–	Plant and supplier
Water scrubbing + regeneration	[11]	200 m^3/h: 0.9 mEUR	–	200 m^3/h: 731	–	Plant data
	[12]	100 m^3/h: 0.5 mEUR 200 m^3/h: 0.7 mEUR	200 m^3/h: 48.4 kEUR/yr 300 m^3/h: 80.6 kEUR/yr	100–200 m^3/h: 702–896	100–200 m^3/h: 0.47–0.53	Plant and supplier
	[12]	2000 m^3/h: 2.6 mEUR	2000 m^3/h: 0.4 mEUR/yr	2000 m^3/h: 219	2000 m^3/h: 0.37	Plant
	[28]	144 m^3/h: 0.3 mEUR	144 m^3/h: 50.0 kEUR/yr	144 m^3/h: 313	144 m^3/h: 0.68	Calculation
	[17]	100 m^3/h: 10.1 kEUR/(m^3/h) 250 m^3/h: 5.5 kEUR/(m^3/h) 500 m^3/h: 3.5 kEUR/(m^3/h)**	100 m^3/h: 14.0 EUR/(m^3/h) 250 m^3/h: 10.3 EUR/(m^3/h) 500 m^3/h: 9.1 EUR/(m^3/h)**	100 m^3/h: 1,030,250 m^3/h: 561,500 m^3/h: 357**	100 m^3/h: 1.44250 m^3/h: 1.06500 m^3/h: 0.94**	Plant + literature
	[14]	100 m^3/h: 5.1 kEUR/(m^3/h) 500 m^3/h: 2.5 kEUR/(m^3/h) 1000 m^3/h: 1.8 kEUR/(m^3/h) 2000 m^3/h: 1.5 kEUR/(m^3/h)	–	100 m^3/h: 867,500 m^3/h: 4,251,000 m^3/h: 3,062,000 m^3/h: 255	–	Supplier
	[55]	600 m^3/h: 2.0 kEUR/(m^3/h)	600 m^3/h: 6.1 EUR cent/m^3	600 m^3/h: 343	600 m^3/h: 6.10	
Cryogenic separation	[28]	161 m^3/h: 0.9 mEUR	161 m^3/h: 0.4 mEUR	161 m^3/h: 960	161 m^3/h: 4.80	Cal
	[55]	600 m^3/h: 2.3 kEUR/(m^3/h)	600 m^3/h: 7.1 EUR cent/m^3	600 m^3/h: 394	600 m^3/h: 7.10	
Physical absorption	[17]	100 m^3/h: 9.5 kEUR/(m^3/h) 250 m^3/h: 5 kEUR/(m^3/h)	100 m^3/h: 13.8 EUR/(m^3/h) 250 m^3/h: 10.2 EUR/(m^3/h)	100 m^3/h: 969 250 m^3/h: 510	100 m^3/h: 1.42 250 m^3/h: 1.05	Plant + literature
		500 m^3/h: 3.5 kEUR/(m^3/h)**	500 m^3/h: 9.0 EUR/(m^3/h)**	500 m^3/h: 357**	500 m^3/h: 0.92**	
	[14]	250 m^3/h: 4.4 kEUR/(m^3/h) 1000 m^3/h: 2.2 kEUR/(m^3/h) 2000 m^3/h: 1.5 kEUR/(m^3/h)		250 m^3/h: 748 1000 m^3/h: 374 2000 m^3/h: 255		Supplier
Chemical absorption	[28]	137 m^3/h: 0.353 mEUR	137 m^3/h: 0.1345 mEUR	137 m^3/h: 438	137 m^3/h: 1.92	Cal
	[17]	100 m^3/h: 9.5 kEUR/(m^3/h) 250 m^3/h: 5 kEUR/(m^3/h) 500 m^3/h: 3.5 kEUR/(m^3/h)**	100 m^3/h: 14.4 EUR/(m^3/h) 250 m^3/h: 12 EUR/(m^3/h) 500 m^3/h: 11.2 EUR/(m^3/h)**	100 m^3/h: 969,250 m^3/h: 510,500 m^3/h: 357**	100 m^3/h: 1.48250 m^3/h: 1.24500 m^3/h: 1.15**	Plant + literature
	[14]	500 m^3/h: 3.3 kEUR/(m^3/h) 1000 m^3/h: 2.4 kEUR/(m^3/h) 1800 m^3/h: 1.6 kEUR/(m^3/h)	–	500 m^3/h: 5,611,000 m^3/h: 4,081,800 m^3/h: 264	–	Supplier
	[55]	600 m^3/h: 2.2 kEUR/(m^3/h)	600 m^3/h: 6.5 EUR cent/m^3	600 m^3/h: 377	600 m^3/h: 6.50	
Pressure swing adsorption	[28]	139 m^3/h: 0.68 mEUR	139 m^3/h: 0.187 mEUR	139 m^3/h: 831	139 m^3/h: 2.63	Cal
	[17]	100 m^3/h: 10.4 kEUR/(m^3/h) 250 m^3/h: 5.4 kEUR/(m^3/h) 500 m^3/h: 3.7 kEUR/(m^3/h)**	100 m^3/h: 12.8 EUR/(m^3/h) 250 m^3/h: 10.1 EUR/(m^3/h) 500 m^3/h: 9.2 EUR/(m^3/h)**	100 m^3/h: 1,061,250 m^3/h: 551,500 m^3/h: 377**	100 m^3/h: 1.31250 m^3/h: 1.05500 m^3/h: 0.92**	Plant + literature
	[14]	500 m^3/h: 2.9 kEUR/(m^3/h) 1000 m^3/h: 2 kEUR/(m^3/h) 2000 m^3/h: 1.5 kEUR/(m^3/h)	–	500 m^3/h: 4,931,000 m^3/h: 3,402,000 m^3/h: 255	–	Supplier
	[55]	600 m^3/h: 2.3 kEUR/(m^3/h)	600 m^3/h: 6.7 EUR cent/m^3	600 m^3/h: 394	600 m^3/h: 6.70	
Membrane technology	[28]	130 m^3/h: 0.233 mEUR	130 m^3/h: 0.1 mEUR	130 m^3/h: 305	130 m^3/h: 1.23	Cal
	[35]	1000 m^3/h: 1.3–2.4 mEUR*	1000 m^3/h: 0.05–0.07 EUR/m^3 **	1000 m^3/h: 289–527	1000 m^3/h: 0.79–1.19	Sim
	[17]	100 m^3/h: 7.3–7.6 kEUR/(m^3/h) 250 m^3/h: 4.7–4.9 kEUR/(m^3/h) 500 m^3/h: 3.5–3.7 kEUR/(m^3/h)**	100 m^3/h: 10.8–15.8 EUR/(m^3/h) 250 m^3/h: 7.7–11.6 EUR/(m^3/h) 500 m^3/h: 6.5–10.1 EUR/(m^3/h)**	100 m^3/h: 760,250 m^3/h: 490,500 m^3/h: 367**	100 m^3/h: 1.11–1.63250 m^3/h: 0.79–1.19500 m^3/h: 0.67–1.05**	Plant + literature
	[14]	100 m^3/h: 6 kEUR/(m^3/h) 300 m^3/h: 3 kEUR/(m^3/h) 700–1400 m^3/h: 2 kEUR/(m^3/h)	–	100 m^3/h: 1,020,300 m^3/h: 510,700–1400 m^3/h: 340	–	Supplier
	[55]	600 m^3/h: 1.8 kEUR/(m^3/h)	600 m^3/h: 5.5 EUR cent/m^3	600 m^3/h: 309	600 m^3/h: 5.50	
In-situ upgrading	NA					
Hydrate formation	NA					
Biological methods	NA					

* Assumption: 1 EUR=9.3 SEK, and 1 EUR=1.3 USD.
** Cleaned gas.

Appendix 4. Biogas upgrading technologies – process diagram examples

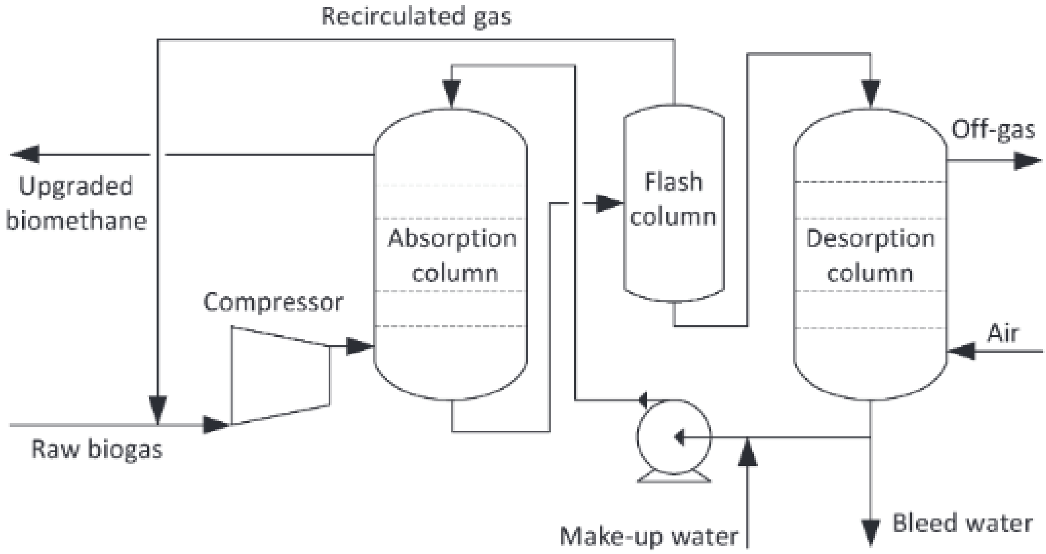

Figure A4.1 Simplified process diagram of a recirculating water scrubber
Source: Bauer et al. (2013)

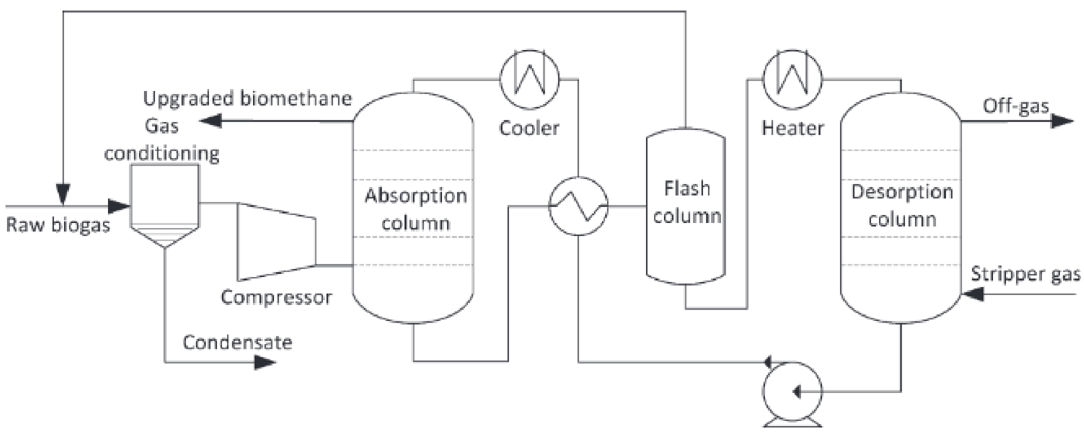

Figure A4.2 Simplified process flow diagram of an organic solvent scrubber
Source: Bauer et al. (2013)

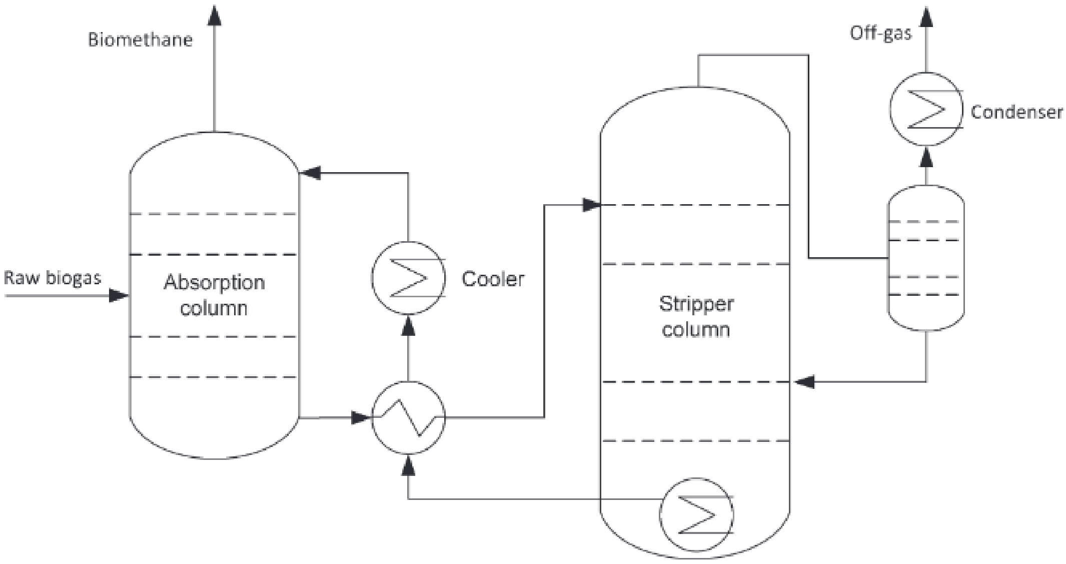

Figure A4.3 Simplified process flow diagram of an amine scrubber
Source: Bauer et al. (2013)

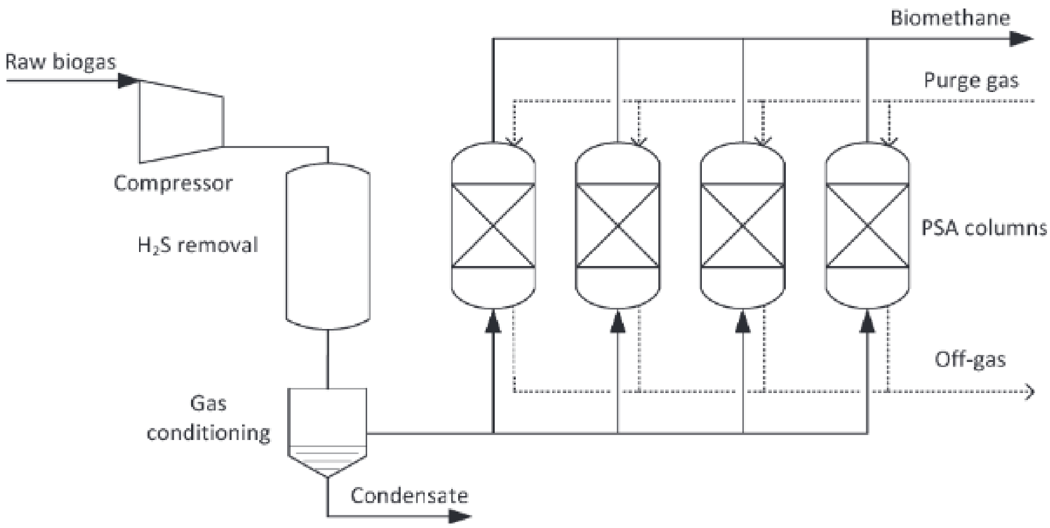

Figure A4.4 Simplified process flow diagram of a pressure swing adsorption unit
Source: Bauer et al. (2013)

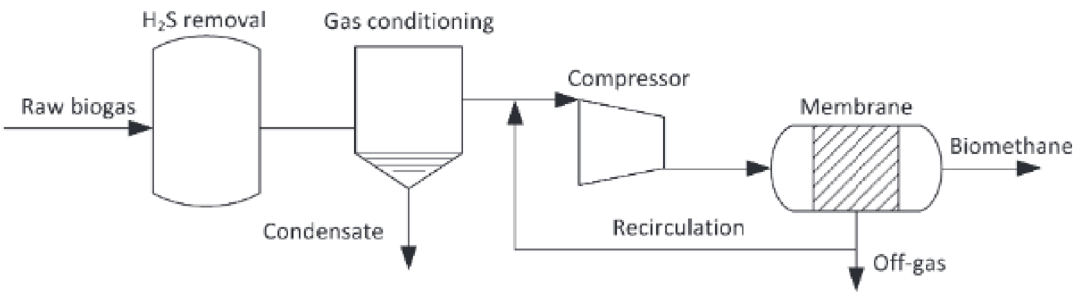

Figure A4.5 Simplified process design for membrane upgrading process
Source: Bauer et al. (2013)

Appendix 5. Workshop exploring the potential for bottled bio-gas for clean cooking in Africa

Rationale

Almost 3 Billion people use biomass, coal or dung for cooking: smoke from fuel combustion contributes to some 4 million premature deaths annually. The United Nations Framework Convention on Climate Change (UNFCCC) Sustainable Development Goals (SDGs) commit countries to improving access to clean energy, but progress is slow. Furthermore, achieving access for poorer people often involves provision of low-power electricity connections, not addressing cooking.

Clean cooking initiatives include efficient solid-fuel stoves, various forms of household-scale waste digestors for biogas, innovations for electricity using batteries and use of bottled gas (notably Liquefied Petroleum Gas , LPG – a clean-burning fossil fuel), all of which have different greenhouse-gas (GHG) emission impacts.

In a scoping study, conducted by partners in the UK, Ghana and Uganda, we have been exploring a different approach, with exciting potential: biogas derived from anaerobic digestion being stored in pressurised containers, similar to those used for LPG, allowing distribution to households. Such approaches are already being implemented in parts of India, but have had little consideration in Sub-Saharan Africa (some studies have been carried out in Nigeria). The project seeks to understand the opportunities for bottled biogas for cooking in Africa, why it has not already taken off, and the key issues to be addressed to enable this.

This workshop will discuss the findings from the scoping study and use those as the basis to consider the need for further research and/or piloting activities. It involves the partners from the scoping study (University of Surrey, Engas UK, KNUST in Ghana and UCPC in Uganda), key sector and policy organisations in Ghana and Uganda, and a small number of additional specialists. The overall aims are to build a consortium of collaborators and to develop the outlines for one or more further studies or activities to pursue bottled biogas in Africa.

The workshop is followed by a 2 day conference, looking at the wider range of options for bringing bio-derived gases to users for cooking. The conference will involve a larger set of participants. The consortium emerging from the workshop may well want to bring in additional collaborators from amongst the conference participants. The workshop and conference is being supported by the new DfiD-funded ‘Modern Energy Cooking services’ programme.

Workshop exploring the potential for bottled bio-gas for clean cooking in Africa

at the University of Surrey, Guildford, UK from 15th to 16th October 2019

Venue: Wates Room, Wates House, University of Surrey, Stag Hill Campus, Guildford, Surrey.

Participants:

Ghana	
Francis Kemausuor	Dept of Agricultural & Biosystems Engineering, KNUST
Ahmad Addo	Head, Dept of Agricultural & Biosystems Engineering, KNUST
Joshua Bright Amenorfe	Secretary, Biogas Association of Ghana
Uganda	
Twinomujuni Edson	Uganda Cleaner production Centre
Joshua Ogwok	Centre for Research in Energy and Energy Conservation
Justine Akumu	Ministry of Energy and Mineral Development
Nigeria	
Fatima Oyiza-Ademoh	Ajima Farms project
University of Surrey, UK	
Matt Leach	Centre for Environment and Sustainability (CES)
Richard Murphy	Director, Centre for Environment and Sustainability (CES)
Jhuma Sadhukhan	Centre for Environment and Sustainability (CES)
Mairi Black	Centre for Environment and Sustainability (CES)
Other UK	
Amit Roy	Engas UK
Dr Aiduan Borrion	UCL
Ms Lucy Hopwood	NNFCC, The Bioeconomy Consultants
Simon Batchelor	MECS

Monday 14th October: Arrival for non-UK delegates; accommodation in a hotel in Guildford

Tuesday 15th October

10.00-10.30 Arrival and coffee

10.30-11.00 Welcome, workshop aims and introductions (Matt Leach, and all)

11.00-12.30 Findings of the scoping study (chaired by Mairi Black):

- Francis Kemausuor, KNUST, Ghana
- Edson Twinomujuni, UCPC, Uganda
- Amit Roy, Engas and Portsmouth University

12.30-1.30 Lunch

1.30-2.30 The key challenges (needs for further work) for bottling biogas

- Facilitated discussions around tables

2.30-3.30 Funding opportunities for research, development and demonstration

- UK sources: Matt Leach and Mairi Black
- National/international sources: all/discussion

3.00-3.30 Tea/coffee

3.30-5.00 Initial outlines of possible research studies and other activities

- Facilitated discussions around tables, based on the key challenges identified

5.00-5.30 Final discussion, plans for day 2, close

7.00- Workshop dinner in Guildford: Olivo Ristorante Italiano

Wednesday 16th October

9.00-9.30 Arrival and coffee

9.30-10.00 Agree on proposals to develop

10.00-11.00 Work on proposals in small groups

- Focus on: challenge to address; methods to use; expected impacts

11.00-11.30 Tea/coffee

11.30-12.30 Continue work on proposals in small groups (switch people round?)

12.30-1.30 Lunch

1.30-2.30 Presentations on each proposal; plenary discussion

2.30-3.30 Focused work on key components of proposals:

- National/international need; Pathways to impact; Gender/inclusivity

3.30-4.00 Tea/coffee

4.00-4.30 Next steps, plans for the conference, close

(Free evening

Appendix 6. Conference exploring portable bio-derived gas for clean cooking in Africa

Rationale

Almost 3 Billion people use biomass, coal or dung for cooking: smoke from fuel combustion contributes to some 4 million premature deaths annually. The United Nations Framework Convention on Climate Change (UNFCCC) Sustainable Development Goals (SDGs) commit countries to improving access to clean energy, but progress is slow. Furthermore, achieving access for poorer people often involves provision of low-power electricity connections, not addressing cooking.

Clean cooking initiatives include efficient solid-fuel stoves, various forms of household-scale waste digestors for biogas, innovations for electricity using batteries and use of bottled gas (notably Liquefied Petroleum Gas , LPG – a clean-burning fossil fuel), all of which have different greenhouse-gas (GHG) emission impacts.

In a scoping study, conducted by partners in the UK, Ghana and Uganda, we have been exploring a different approach, with exciting potential: biogas derived from anaerobic digestion being stored in pressurised containers, similar to those used for LPG, allowing distribution to households. Such approaches are already being implemented in parts of India, but have had little consideration in Sub-Saharan Africa (some studies have been carried out in Nigeria). The project seeks to understand the opportunities for bottled biogas for cooking in Africa, why it has not already taken off, and the key issues to be addressed to enable this.

Associated with the study of bottled biogas, this conference will explore the opportunities for clean cooking with biomass-derived gases more generally, including biogas from anaerobic digestion, bottled as above, bio-LPG (bio-propane) derived from biodiesel production, and other potential routes. The conference will bring together researchers, the private sector, NGOs and policymakers to explore the current experience internationally with such approaches for clean cooking, the opportunities ahead and the barriers that need to be dismantled. The conference is being supported by the new DfiD-funded 'Modern Energy Cooking services' programme, and will comprise leading practitioners and researchers internationally.

Please contact Mairi Black, m.black@surrey.ac.uk for further information.

Portable bio-derived gas for clean cooking

at the University of Surrey, Guildford, UK from 17th to 18th October 2019

Venue: Treetops, in Wates House, University of Surrey, Guildford, Surrey

Wednesday 16th October

Arrival for non-UK delegates; accommodation to be provided in a hotel in Guildford

Thursday 17th October

9.30 Arrivals

10.00-10.30 Welcomes; brief outline of MECS; outline of the biogas bottling project at Surrey (Matt Leach/Mairi Black/Simon Batchelor)

10.30-11.50 Session 1: Biogas Overview – Ghana, India and Uganda (led by Prof. Matt Leach)

- Mr. Joshua Bright Amenorfe, Biogas Association of Ghana, Overview of biogas developments and industry in Ghana, (20 mins)
- Mr. Atma Ram Shukla, Indian Biogas Association, Overview of biogas developments and the industry in India (20 mins)
- Mr. Edson Twinomujuni, UCPC, Uganda, Overview of biogas developments and the industry in Uganda (20 mins)

11.50-12.10 Tea/coffee

12.10-1.00 Session 2: Routes for biomass to gas for clean cooking (led by Jhuma Sadhukhan, Surrey)

- Mr. Amit Roy, Engas and Portsmouth University, Innovation in small scale production and compression technology (10 mins)
- Prof. Virendra K. Vikray, Center for Rural Development and Technology, India, Bio-CNG Experience in India (20 mins)
- Mr. Kimball Chen, GLPGP, Bio-LPG: technologies and prospects (20 mins)

1.00-2.00 Lunch

2.00-3.00 Session 3: Bio-CNG opportunities in Africa: Ghana and Uganda case studies (led by Richard Murphy, Surrey)

- Dr. Francis Kemausuor, KNUST, Ghana: current activities, commercial interest (20 min)
- Mr. Edson Twinomujuni, UCPC, Uganda: current activities, commercial interest (20 mins)
- Mr. Amit Roy, Engas and Portsmouth University, Business model analysis for bio-CNG: initial results (20 mins)

3.00-4.00 Session 4: Bio-gas cooking experience in other parts of Africa and Asia (led by Matt Leach, Surrey & MECS)

- Ms. Fatima Oyiza-Ademoh, Ajima Farms, Off-grid energy project, Nigeria (20 mins)
- Zacchariah BBOXX, Biogas in Rwanda (20 mins)
- Joel Chaney & Charlotte Ray, CREATIVenergie, Bottling biogas in Tanzania (title to be updated) (20 mins)

- Jon Cloke, MECS and LCEDN, Biogas in Bangladesh (20 mins)

4.00-4.30 Tea/coffee

4.30-5.30 Session 5: Opportunities and challenges: Biogas production/AD (led by Onesmus Mwabonje, Imperial College London)

- Mr. Michael Chesshire, REA/Lutra, UK experience in the development of AD operations and biogas markets – opportunities and challenges (20 mins)
- Mr. Joshua Ogwok, Centre for Research in Energy and Energy Conservation, Uganda (20 mins)
- Rokiah Yaman, LEAP Micro AD, Micro AD: advantages and challenges of decentralised biogas production (20 mins)

5.00-5.30 Discussion. Thanks, plans for day 2, close

6.30- Conference dinner in Guildford

Friday 18th October

9.00 Arrivals

9.30-9.45 Welcomes, plan for the day

9.45-11.00 Session 6: Key barriers/issues in implementing portable bio-gas (led by Mairi Black, Surrey)

- Dr. Sarah Hunter, UCL, Feedstock types and scales (20 mins)
- Paula Edze, Coordinator, Sustainable Energy for All Secretariat, Ghana (20 mins)
- Elisa Puzzolo, GLPGP, Bio-LPG: regulations and safety (20 mins)

11.00-11.30 Tea/coffee

11.30-12.00 Mr. Thomas Minter, World Biogas Association and Malaby Biogas Ltd, The Global Potential of Biogas. Insights into scale and delivery and applications (30 mins)

12.00-1.00 Roundtable discussions

1.00-2.00 Lunch

2.00-3.00 Session 7: Policy and investment support

- Mr. Julius Nkansah-Nyarko, Energy Commission Ghana, Technical regulation and policy formulation (20 mins)
- Ms. Justine Akum, Ministry of Energy and Mineral Development Uganda, Policy approach Uganda (20 mins)

3.00-4.00 Final discussion

4.00 Thanks and close