Bioenergy for Sustainable Energy Access in Africa

PO 7420

Technology Value Chain Prioritisation Report

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by LTS International Limited, the University of Edinburgh and E4tech

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Acronyms

BSEAA	Bioenergy for Sustainable Energy Access in Africa
C(C)HP	Combined (Cooling,) Heating and Power
DFID	Department for International Development
EEP	Energy and Environment Partnership programme for East & Southern Africa
EPC	Engineering, Procurement and Construction
OPEC	Organization of the Petroleum Exporting Countries
REACT	Renewable Energy & Adaptation to Climate Technologies
SSA	Sub-Saharan Africa
TRL	Technology Readiness Level
TVC	Technology Value Chain
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organisation

Contents

EXECUTIVE SUMMARY **1**
1. INTRODUCTION **7**
2. METHODOLOGY **8**
2.1 WEB-BASED RESEARCH 8
2.2 DIRECT INTERACTION 9
2.3 TVC PRIORITISATION PROCESS 10
3. FINDINGS **11**
3.1 INTRODUCTION 11
3.2 ANAEROBIC DIGESTION 12
3.3 GASIFICATION 26
3.4 COMBUSTION 39
4. CONCLUSIONS **44**
5. NEXT STEPS **45**

Annexes

ANNEX A GOOGLE SEARCH STRINGS FOR TVCS 48
ANNEX B PEOPLE CONSULTED DURING THIS PHASE 49
ANNEX C TVC EXAMPLES BY TECHNOLOGY TYPE AND COUNTRY 52
ANNEX D FEEDSTOCK CLASSIFICATION FOR TVCS 60
ANNEX E BIBLIOGRAPHY 61

Executive Summary

Introduction

LTS International, the University of Edinburgh and E4tech are implementing Phase I of the Bioenergy for Sustainable Energy Access in Africa (BSEAA) study. BSEAA is investigating the opportunities and challenges for the roll-out of bioenergy technology in Sub-Saharan Africa (SSA) and supporting the development of innovative bioenergy solutions.

In the first phase, the team identified ten promising countries and three technologies for more in-depth investigation:

a) Anaerobic digestion-to-internal combustion engine
b) Gasification-to-internal combustion engine
c) Combustion-to-steam turbine.

The current phase aims to prioritise particular 'Technology Value Chains' (TVCs) that combine these technologies with certain feedstocks and end uses, and offer potential for replication. The next phase will explore those TVCs in more depth through a case study approach, in order to identify specific opportunities for research-led innovation.

Methodology

Earlier stakeholder mapping had indicated that the number of TVC examples attempted thus far in SSA were likely to be limited. Rather than speculate about theoretical TVCs for which the chances of adoption would be negligible, the team therefore decided to base the analysis on the relatively few options for which there has been a least one operational example, successful or otherwise. It was therefore agreed that a shortlisted TVC for each technology should have been attempted in at least one verifiable example in SSA within the last decade (above household scale but below the agreed 5 MW threshold) and ideally also offer evidence of success outside Africa. Systematic web searches were carried across 29 English and French-speaking countries in SSA and six Newly Industrialised Countries to identify qualifying TVC examples for each technology. A parallel investigation was undertaken of project developers, technology providers, energy initiatives, research organisations and funding agencies. Technical and operational details were verified through direct contact with nearly 70 individuals.

Findings

Introduction

The research generated a database of 153 TVC examples in SSA, though fewer than 100 installations were actually constructed and a majority are no longer believed to be functioning, especially among the gasification projects. At the community-to-5 MW scale, even project developers and financiers specifically interested in developing bioenergy energy opportunities in Africa have supported few initiatives beyond feasibility assessment. Scattered examples in the desired technology areas and scale range were often supported by donor-funded grant programmes.

Anaerobic Digestion

45 examples were identified in SSA of **anaerobic digestion systems linked to gas or dual-fuel engines** for heat, power or cooling services. 12 are functioning and a similar number with unclear status may also be operational. Energy output was split roughly equally between large (>1 MW), medium (0.1-1 MW) and small (100 kW) installations. The functional projects are all located in livestock farms or agribusinesses. No successful anaerobic digestion projects for combined cooling, heating and power (C(C)HP) were found in community-managed settings.

The most common biogas feedstocks are **animal by-products**. South Africa dominates with at least five plants using cattle dung to power captive grids above 1 MW, while smaller units are found in Namibia, Kenya and Uganda. Projects in Nigeria, South Africa and Botswana use poultry or pig manure. There have been a handful of biogas-to-power projects using abattoir waste, with examples from 275 kW to over 5 MW in Burkina Faso, Senegal and Ghana. Two biogas-powered electricity systems were also installed at abattoirs in Kenya, though one 10 kW_e system is not functional and the other uses the gas for cooking instead of meat refrigeration as intended.

There have been numerous feasibility studies for anaerobic digestion systems generating heat or power from **municipal by-products,** but no installation in SSA currently or recently functional could be identified.

The remaining examples of anaerobic digestion operate using various **agricultural wastes**. The largest and most successful are in Kenya, including a 2.8 MW system using vegetable processing waste, a 160 kW_e/170 kW_{th} plant using mainly spent tea and a 300 kW system using avocado processing waste. Other agri-businesses have invested at scattered sites, including a 1.2 MW plant in Gabon using palm oil mill effluent, a 300 kW system in Tanzania using sisal waste, a (now closed) containerised biogas plant in Côte d'Ivoire using cocoa shells and two proposed plants in South Africa, one using Napier Grass with sugarcane tops and trash, and the other using fruit processing waste.

Experience from selected Newly Industrialised Countries

There has been rapid growth of anaerobic digestion in several Newly Industrialised Countries. Tax-incentives, feed-in tariffs and government subsidies have often played a catalytic role. There are promising indications of transferability potential to Africa (based on feedstock flexibility and scalability, among other things), but also a likely need for financial incentives to kick-start investment This is especially the case for smaller projects that developers may find less attractive.

Summary – Anaerobic Digestion

Anaerobic digestion is a well-developed technology that has been widely adopted globally for C(C)HP. An accelerated uptake can be anticipated in SSA, based on early adoption by livestock and agri-businesses in South Africa and Kenya that use mainly German technology. These early adopters usually own the feedstock and use the energy and slurry themselves. There is innovation potential around the development of cheaper and more durable materials for digesters, direct cooling applications, lower-cost control systems for small-scale heat and power production, and potential expansion to Africa-specific feedstocks. DFID research support could be well timed.

The most promising feedstocks are municipal by-products, animal wastes and the by-products of agricultural processing, for which a selection of specific crops is proposed, based on replication potential in the shortlisted countries. The greatest challenge for DFID may lie in finding business models that are pro-poor but can at the same time be realistically managed within the capacity of communities and mid-sized farms and industries.

Gasification

47 examples were identified in SSA of **gasification plus internal combustion engine**, to deliver heat, power or cooling services. Of the 13 projects that have reached implementation stage, no more than seven are believed to be operational and four of these - two in Uganda, one in Benin and one in Nigeria - operate only intermittently. Two in Ghana have only been operating for a month. Unlike anaerobic digestion, the majority of the working gasifier projects are below 100 kW_e and have been installed at community level or in small-scale productive settings.

Around two thirds of the 47 projects use **agricultural or agro-industrial by-products** as feedstock, while the remainder use **woody by-products or forest/plantation wood**. The four largest projects (above 1 MW_e) all rely on woody biomass, which is the dominant feedstock globally for this technology.

Of 18 TVC examples that use agricultural by-products, just three are operational and use gasifier technology from India. These include two in Uganda fuelled with maize cobs to feed local mini-grids and one (500 kW_e) in Tanzania using rice husk. Four projects in the planning stages also intend to use agricultural residues, one 50 kW_e plant in Uganda using maize cobs and rice husk, a 32 kW_e project in Tanzania also using rice husk, a 75 kW_e project in Tanzania using cashew shells and a project in Mozambique to supply a hybrid mini-grid using cotton residues. Eight projects that are either abandoned, shut down or not operational also use(d) agricultural residues. The status of three projects using maize cobs, rice husk and cotton residue pellets is unclear.

A new (February 2017) 20 kW_e gasifier in Ghana uses palm kernel shells, and there is a gasifier using sisal waste in Kenya that may have closed. A 32 kW gasifier in Benin uses a mix of tree prunings, rice husk and palm kernel cake, and a 120 kW_e system is being developed in Tanzania using agricultural waste and forestry residue.

The only operating project using forest or plantation wood directly is a 32 kW_e gasifier in Nigeria fired by wood-chips to provide electricity to rice and flour mills. Seven other projects using these feedstocks are either under construction, shut down or have an unclear status. These include the largest gasification project in SSA, a 2.4 MW_e venture in Kenya that will use wood chips from invasive *Prosopis juliflora*, once gas cleaning problems are resolved.

Three projects that used wood residues have been decommissioned, one 180 kW_e unit at a tea estate in Uganda using eucalyptus blocks, a 250 kW_e gasifier in Namibia using invader bush and a 10 kW_e gasifier in Uganda using eucalyptus prunings. Seven gasification projects using by-products from wood processing were identified in SSA. One is planned, one has shut down and the status of the other five is unclear.

Experience from selected Newly Industrialised Countries

Small-scale biomass gasification has been introduced at a range of scales in India, Thailand, Indonesia, the Philippines and Brazil, often with the support of governments and development agencies. Gasification linked to rice mills, coconut farms or wood processing enterprises has in theory offered a model that ensures reliable supply of feedstock and an anchor load for the power, with the potential for selling surplus to the grid. Projects have encountered challenges, however, related to consistency of feedstock supply, high tar content in the gas, high demand for water and disposal of that water once contaminated. A lack of qualified operators has also contributed to failure. While India has led the way in small-scale gasification and offers transferability lessons for Africa, there is limited evidence of long-term operation at community level.

Summary - Gasification

Small-scale gasification at <100 kW_e represents one of the only technologies capable of producing electricity from agricultural by-products at a reasonable level of efficiency. Results have been mixed in Asia, however, and the team could not identify any gasification projects in SSA that have been operating reliably over a period of years. Reliability is hampered by lack of technical capacity, stringent feedstock requirements, high tar content of the syngas and contamination of cleaning water. Only very few medium scale gasification projects (1 to 5 MW_e) were identified, giving no foundation on which to scale-up and replicate.

No gasifier technology provider has a successful track record in SSA. While sophisticated US and European equipment lacks local technical back-up and spares, the long-term reliability of simpler and more robust systems from India cannot be verified. This opens up potential innovation opportunities in developing simpler technology, workable business models that are realistically manageable within the capacity of small-scale industries, and building up suitable local technical and engineering capacity. The feedstocks worth pursuing for technical viability and replication potential are woody materials from trees and processing by-products, as well as the residues from specific widespread crops.

Combustion

Biomass combustion systems powering steam turbines are mostly found in bagasse-fuelled power plants in sugar mills, where this technology is well established above the 5 MW level. Discounting these large scale examples, there are fewer than ten steam turbines linked to combustion systems in SSA, one 640 kW_e plant in Côte d'Ivoire fed with **palm oil waste** and the others all fuelled with **woody biomass**.

The largest installations in SSA are found at forestry operations, with a 2.5 MW_e example in Tanzania fuelled with eucalyptus and pine wastes and a smaller (700 kW) plant using eucalyptus feedstock at a tea estate in Kenya. A 1.1 MW steam turbine plant fuelled with sawmill waste is planned in Cameroon and a larger (6 MW) plant for the forest industry in Ghana's Ashanti Region. On Mafia Island in Tanzania, a 1 MW_e steam turbine fuelled with coconut wood provides power for a mini-grid. One smaller example was an EU-funded 75 kW installation in Madagascar using community-owned forest plantation waste.

These installations tend to be large, employ proven technologies from well-known suppliers and represent straightforward investment decisions by commercial players based on known operating parameters.

Summary

Combustion powering steam turbines is a well-developed technology combination with limited technology innovation potential. The majority of larger-scale (mostly >5 MW_e) installations in SSA are located at sugar mills using bagasse, while others use wood processing by-products and plantation wood. It had been thought during the previous phase that uptake of this technology might have been impeded by the absence of lower capacity, off-the-shelf turbine systems for sub-5 MW applications. Further investigation has revealed, however, there are a number of technology providers already offering compact steam turbines with outputs in the hundreds of kW, so the technology innovation potential is lower than anticipated.

A piece of desk-based research in the next phase will investigate opportunities for further uptake in agricultural, agro-industrial and forestry industries in the 250 kW_e to 1 MW_e range. The technology is inefficient for power-only generation at these small scales, so there would need to be demands for cogeneration.

Conclusions and next steps

Anaerobic digestion is the most promising technology for case study research. There is innovation potential in technology, feedstocks and business models. The commercial biogas sector is seeing growing investment in SSA to which DFID could add impetus through targeted research. The technology has high adoption levels outside the continent from which to draw lessons and 'leapfrog' technologically, significant feedstock flexibility across municipal, agricultural and livestock waste streams, a relatively passive mode of fuel production (not requiring full-time management), dispatchability of the energy and co-benefits from waste disposal and digestate production.

Gasification has an inconsistent track record at small output scales. State of the art systems are complex to maintain, while simpler technologies are proving polluting and unreliable. Failure rates in SSA are close to 100%, mainly due to problems with gas quality and lack of maintenance expertise and spare parts. Nevertheless, further research into the small number of plants known to exist in SSA could reveal areas for potential research support.

There are no **steam turbine** installations at small scale, therefore no opportunity for case study analysis. Desk research will instead be conducted into the technical and economic feasibility of sub-1 MW heat or power applications and potential innovation opportunities that may exist.

During the next phase of work, case studies of anaerobic digestion and gasification will be selected that provide working examples of the prioritised TVCs from which to draw experiences and lessons. These will be described in Case Study Reports that identify the main barriers and opportunities for replication and innovation, and give an indication of the areas of research that DFID might usefully support in BSEAA Phase II.

1. Introduction

LTS International has teamed up with The University of Edinburgh and E4tech to implement Phase I of the DFID-funded Bioenergy for Sustainable Energy Access in Africa (BSEAA) research assignment. BSEAA is investigating the challenges and opportunities affecting the adoption and roll-out of bioenergy across Sub-Saharan Africa (SSA) and supporting the development of innovative bioenergy solutions for developing countries. Phase I runs for 12 months from September 2016 and is intended to identify areas of potential innovation in bioenergy technology or related value chains in SSA for more targeted research in Phase II. Phase II will be part of DFID's larger Transforming Energy Access programme, which seeks to test innovative technology applications and business models to accelerate the provision of affordable, clean energy-based services to poor households and enterprises.

A six-week Design Phase during September and October 2016 resulted in finalisation of the BSEAA research methodology, results framework, work plan and research question: "Which bioenergy technologies have the greatest potential for uptake at scale in Sub-Saharan Africa?".

Literature review and stakeholder mapping during the first substantive phase (from November 2016 to January 2017) led to the shortlisting of three promising technology combinations for biomass conversion (anaerobic digestion-to-internal combustion engine, gasification-to-internal-combustion-engine and combustion-to-steam turbine) and ten priority countries[1] for more detailed research.

The current phase (February to March 2017) involves the prioritisation of particular 'Technology Value Chains' (TVCs) that incorporate the shortlisted technologies. A TVC is characterised by a particular combination of biomass input, conversion process and energy application. So while the previous phase reduced the scope of the study to a shortlist of potentially suitable technologies, independent of location, feedstock or business model, the current phase has sought to identify specific value chains that offer the greatest potential for widespread uptake of those technologies.

During the next phase (May to July), the study team will identify representative examples of the prioritised TVCs. These will be used as case studies for analysing barriers and opportunities to wider replication in SSA within the defined technology areas. This analysis will in turn guide the development of the final research framework for BSEAA Phase II that will be delivered by the end of August.

[1] Ethiopia, Ghana, Kenya, Mozambique, Nigeria, South Africa, Tanzania, Uganda, Rwanda and Zambia.

2. Methodology

2.1 Web-based research

During this phase of work, team members conducted extensive web-based research to catalogue examples of bioenergy initiatives that incorporate the shortlisted technologies, in both Africa and a sample of comparator countries.

Systematic searches were undertaken via Google, using standardised search strings, to identify both feasibility studies and actual bioenergy installations in each of the ten prioritised SSA countries over the last decade. The search was extended to 19 additional English and French-speaking SSA countries that looked promising based on population size, wealth and suspected existence of bioenergy projects (according to the earlier stakeholder mapping and literature review). Six Newly Industrialised Countries outside Africa were also researched to identify TVCs with transferability potential to Africa. See Table 1 for the full list of countries investigated through the Google-based search.

Table 1. Countries systematically investigated for TVC examples

Priority SSA countries	Other SSA countries		Newly Industrialised Countries
	Anglophone	Francophone	
Ethiopia Ghana Kenya Mozambique Nigeria South Africa Tanzania Uganda Rwanda Zambia	Botswana Lesotho Malawi Namibia Sudan Swaziland Zimbabwe	Benin Burkina Faso Cameroon Congo, Dem. Rep. Congo, Rep Côte d'Ivoire Gabon Guinea Madagascar Senegal Togo	Brazil India Indonesia Malaysia Philippines Thailand

The following search strings were applied for each technology in each country:

primary technology (e.g. biogas)

+

secondary technology (e.g. combustion engine)

+

country (e.g. Kenya)

The specific search strings can be found in Annex A. Where a search brought up an excess of results (>100,000) or if the results were generic and not focused on specific operational examples, then further terms such as 'project', 'feasibility study' or 'case study' were added to fine tune the search. Equivalent search strings in French were used for the 11 Francophone countries (again, see Annex A).

A standard set of data was gathered for each TVC example identified through Google and recorded in an Excel-based TVC grid. Data included location, project developer, technology provider, plant capacity, feedstock, energy application, funding source, operating status and URL(s) for information sources.

The Google-based searches were complemented by a parallel investigation via the websites and web-accessible publications of specific organisations known to be working on bioenergy in SSA. This was based on the comprehensive list of project developers, technology providers, multilateral energy initiatives, research organisations and funding agencies that had been assembled during the earlier stakeholder mapping exercise. The list was extended during this phase as promising leads were explored and new contacts made. African TVC examples identified through this web-based research were added to the same master grid or used to elaborate existing entries.

By searching for TVC examples both via Google research and through guided investigation of organisations already known to be supporting or developing bioenergy projects in SSA, the team generated two streams of results that could be cross-checked for duplication and overlap, giving confidence that all relevant TVC examples had eventually been identified.

2.2 Direct interaction

African TVC examples from the master grid were reviewed one at a time to confirm quality, consistency and reliability of information. The work of the team members who had conducted the Google-based searches was cross-checked for accuracy by the senior consultants conducting the organisation-based research. Data gaps were filled, the operating status of each project was queried and technical details were cross-checked. The aim was to ensure a reliable dataset of projects known to have progressed beyond the feasibility stage and actually been constructed, and as far as possible to ascertain the outcome of each investment and its current status.

Inevitably this required direct contact with a variety of project developers and technology providers. Team members communicated via email, Skype, phone and in person with nearly 70 individuals (listed by name in Annex B). This enabled information gathered from the web to be confirmed and supplementary technical and operational details to be ascertained, while anonymising confidential technical or financial data where requested. It also opened up channels of direct communication for researching the barriers and opportunities for mid-scale biomass-based energy projects that will be explored in the next phase through case study profiling.

2.3 TVC Prioritisation Process

The aim of this phase of the assignment was to prioritise TVCs for case study analysis between May and July (subject to the cooperation of implementers on the ground).

It became apparent through the research that the range of attempted projects and TVC examples in SSA is somewhat limited; the barriers to investment and sustainable implementation appear to be significant. With myriad challenges already being faced by developers of existing opportunities, any exploration of speculative TVCs not yet conceptualised, for which the chances of successful adoption would be negligible, would lead only to abstract analysis of theoretical barriers and opportunities. In order to prioritise TVCs based on grounded research, the team therefore resolved not to speculate on the uptake potential of notional combinations of feedstocks, technologies and energy applications that might potentially work in Africa. They instead identified options for which there has already been a least one operational example in the region, successful or otherwise, on which to base the analysis.

The following qualifying factors were applied in this process of TVC prioritisation:

a) A TVC should include one of the three shortlisted technology combinations: anaerobic digestion-to-internal combustion engine; gasification-to-internal combustion engine; or combustion-to-steam turbine.

b) A TVC should have been attempted in at least one verifiable operational example in SSA within the last decade.

c) The TVC example should have operated above household scale but below the 5 MW ($_e$ or $_{th}$) output threshold that was agreed in the study Design Phase.

d) There should ideally have been examples of the TVC succeeding outside Africa, preferably in a Newly Industrialised Country, indicating some potential for adaptation and transfer.

3. Findings

3.1 Introduction

The research generated a database of 153 TVC examples in SSA and a further 98 from the sampled Newly Industrialised Countries. However, 25 of the SSA examples were only feasibility studies and a further 31 were above the 5 MW output threshold. This means that fewer than 100 projects across the three technology areas were actually constructed , with a majority of these no longer believed to be functioning.

This finding reveals a surprising paucity of investment. Even among project developers and financiers specifically interested in developing bioenergy energy opportunities in Africa, the number of initiatives that have progressed beyond feasibility assessment has been extremely limited at the community-to-5 MW scale. For example, none of the following prominent organisations with renewable energy interests and specific funding windows for bioenergy appear to have supported bioenergy projects in SSA within the desired scale range and technology areas:

- the USD 8.1 billion **Climate Investment Funds** of the multilateral development banks to scale up deployment of renewable energy solutions, which include the $5.8 billion **Clean Technology Fund** to promote low carbon technologies and the Strategic Climate Fund, which in turn incorporates the USD 500 M **Scaling-Up Renewable Energy Programme**;
- the GBP 78 M **Green Africa Power** fund of DFID and the UK Department for Business, Energy and Industrial Strategy;
- DFID's GBP 48 M **Renewable Energy Performance Platform,** managed by Camco Clean Energy and Greenstream[2];
- the USD 95 M **Sustainable Energy Fund for Africa** supported by Denmark, UK, USA and AfDB;
- the **Africa Renewable Energy Access Programme** of the World Bank's Energy Sector Management Assistance Programme;
- the **Sustainable Energy for All** initiative of the African Development Bank, African Union, NEPAD and the UN Development Programme; and
- a range of private and quasi-private renewable energy investment vehicles, including Vantage GreenX, responsAbility Energy Access, Inspired Evolution

[2] The Renewable Energy performance Platform Manager was interviewed and is screening his portfolio, but has so far not confirmed any bioenergy investments.

Investment, GuarantCo, the Danish Climate Investment Fund, DI Frontier Investment and the InfraCo Africa Sub-Sahara Infrastructure Fund.

Any bioenergy investments tend to have been directed towards well-proven TVCs at industrial scale - such as the USD 7.1 M support for a 20 MW bagasse-to-power plant at Kakira Sugar in Uganda co-financed by Norway, Germany, the United Kingdom and the European Union through the GET FiT Programme (GETFiT Uganda, 2016). Perceived risks, especially around feedstock reliability, may have steered investors towards only the highest Technology Readiness Level (TRL) technology options. The relatively small number of concrete examples informed the team's decision to restrict the analysis to actual TVCs that are known to have been attempted, and not to speculate about untested TVCs that might theoretically be configured using feedstocks available in Africa.

There are nevertheless scattered examples of bioenergy projects in the desired technology areas and scale range that have gone ahead in SSA, and these are described in the sections that follow. Grant-making programmes mentioned in the previous phase of this assignment – such as **Powering Agriculture**, the **African Enterprise Challenge Fund**'s 'REACT' window[3] and the **Energy and Environment Partnership** (EEP) programme for East and Southern Africa – have played a key supporting role.

The report continues by profiling those TVCs that *were* found to have been developed into operational projects, addressing each of the three technology areas in turn. A full list of the TVCs by technology type and country is provided in Annex C. An additional list of TVC examples from the selected Newly Industrialised Countries is too long to be included, but is available on request from the authors.

3.2 Anaerobic digestion

3.2.1 TVC descriptions

Project overview and status

In SSA, 58 examples were identified of **anaerobic digestion systems linked to gas or dual-fuel engines** to deliver heat, power or cooling services. The list was reduced to 45 after discounting feasibility studies that are yet to be followed through (see Table 2).

[3] Renewable Energy and Adaptation to Climate Technologies.

Table 2. Anaerobic digestion projects identified in SSA <5 MW

Status	No.
Feasibility study	13
Operational	13
Under construction	2
Planned	10
Abandoned/shut down	4
University research pilot	6
Status unclear	10
Total	**58**

13 of these installations are known to be functioning and 10 had an unclear operational status. The remainder are academic research projects (6), systems planned or under construction (12) or units confirmed closed or abandoned (5).

Energy output range

Energy output could be determined for about three-quarters of the projects (Figure 1). The split was roughly equal between large (>1 MW), medium (0.1-1 MW) and small-scale (<100 kW) projects.

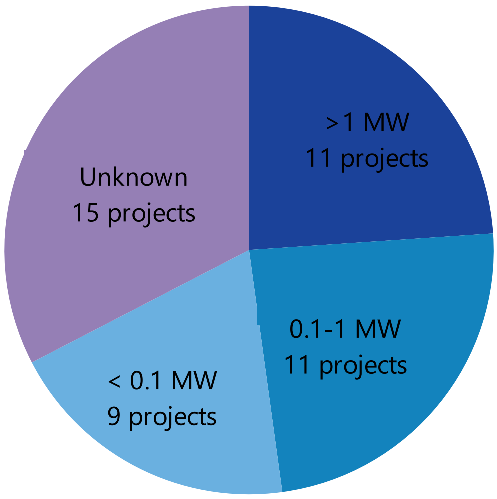

Figure 1. Scale range of anaerobic digestion TVC examples (excluding feasibility studies)

TVC profiles

The identified TVCs are summarised with associated feedstock streams in Figure 2 below. The feedstocks have been categorised using a modified version of the FAO Unified Bioenergy Terminology definitions (FAO, 2004). For details see Annex D. Note that 'agricultural by-products' are classified differently here from 'agro-industrial by-products', to make the distinction between processing wastes from staple food crops (such as rice, maize or potato) and those from other agricultural commodities (such as tea, sisal, sugar cane, palm oil and cocoa).

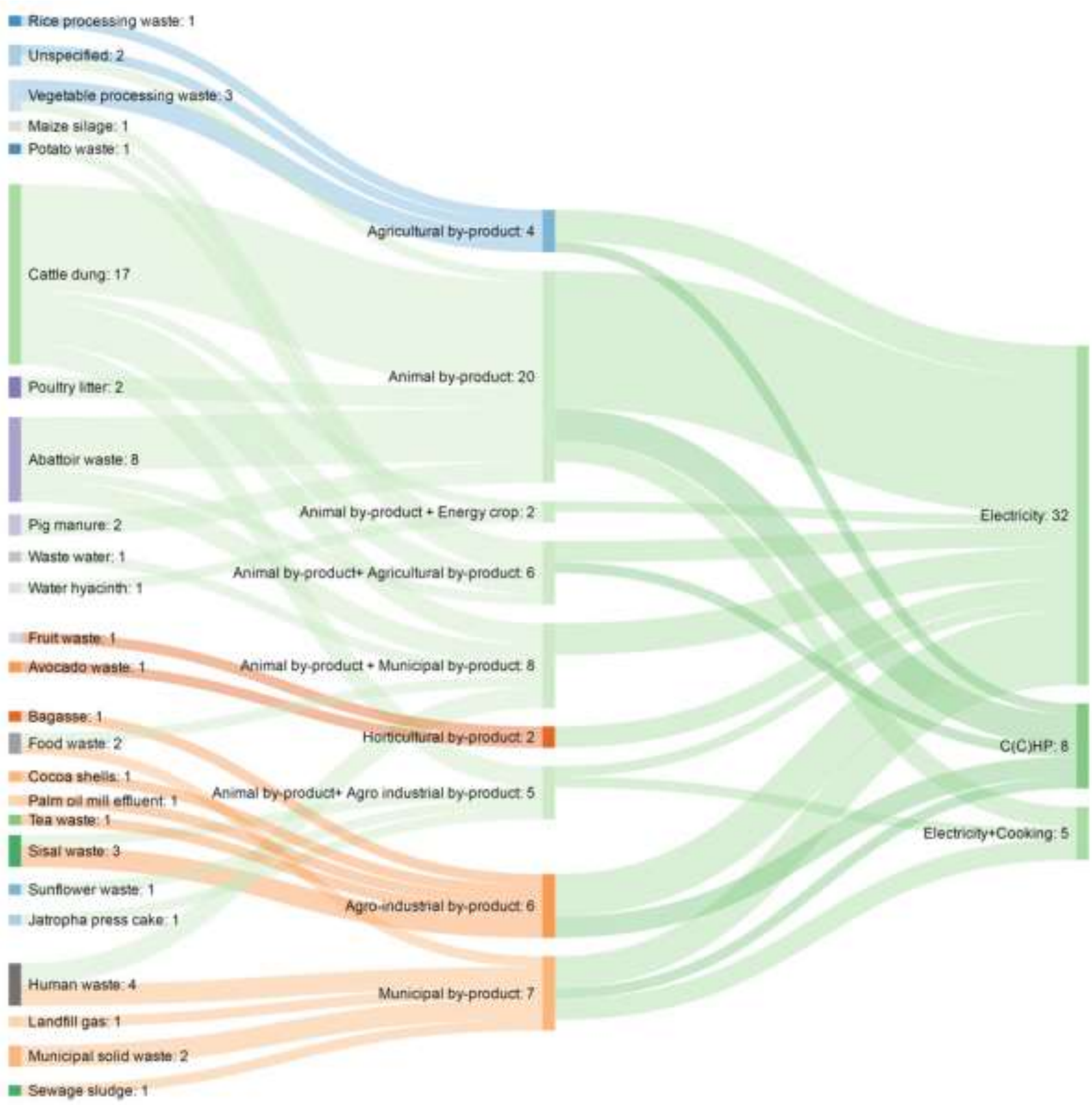

Figure 2. TVC profiles for anaerobic digestion + internal combustion engine

Animal by-products

As the diagram shows, the feedstocks with highest representation in anaerobic digestion TVCs are unsurprisingly **animal by-products**, most commonly cattle dung and abattoir waste.

Those systems running purely on **cattle dung** are predictably found at ranches and dairies, with ten examples identified across Africa. Five of these are in South Africa and designed for large power outputs ranging from 2.2 MW_e (Dundee Power in KwaZulu-Natal) to 4.8 MW_e (Bio2Watt near Pretoria). Biogas-to-power seems reasonably well developed on South African farms for captive grids, as tariffs for grid feed-in are reportedly below US 8 cents/kWh and uneconomic (Boshoff, 2017).

The South African ventures tend to have a significant proportion of private finance. For example, a 500 kW installation by Cape Advanced Engineering at Uilenkraal Dairy Farm at Darling in the Western Cape was funded entirely by the owners, (Engineering News, 2015); the Bio2Watt plant at Bronkhorstspruit near Pretoria was financed by a combination of a government grant, a loan from the Industrial Development Corporation and various equity investors (Bio2Watt, 2016); and a biogas power plant at Manjoh Ranch at Nigel in Gauteng was part-financed by Farmsecure Carbon under the Clean Development Mechanism (South Africa Dept. of Energy, 2011). Though the projects are not numerous, the nature of financing indicates that these ventures are commercially viable in South Africa under the management of mid-sized agribusiness, where there is captive demand for the heat or power produced.

Bio2Watt Bronkhorspruit biogas plant, South Africa

Nearby in Namibia, the Aimab 'Super Farm' run by Namibian Dairies also reportedly installed a biogas-powered generation system (The Namibian, 2009). Outside southern Africa, the cattle industry is smallholder-dominated and the waste is less centralised, offering fewer opportunities for large-scale biogas-powered C(C)HP plants using this particular feedstock. Only one example using cattle dung was found outside southern Africa, at a dairy and sisal estate on the Kenyan coast (Biogas Power Holdings (EA), 2009). This joint venture of Kilifi Plantations and the German companies agriKomp and Schnell Zündstrahlmotoren received GIZ support to install a 150 kW_e system fuelled with **sisal waste and cattle dung**. The cost of electricity production was reportedly EUR 0.16 per kWh, whereas grid electricity costs EUR 0.15-0.18, so feed-in was of marginal interest and the power is used within the farm (Energypedia, 2015a). A 12 kW biogas-power system using cattle dung supplemented by invasive **water hyacinth** was set up on the Ssese Islands in Lake Victoria, Uganda by local project developer GRS Commodities. With financing from the FACT Foundation and the University of Wageningen, and equipment from Albers Alligator (Netherlands) and Weifang Chaoran Gas Power Company (China), a plug-flow digester generated electricity for charging batteries and powering a rice mill (SNV & FACT Foundation, 2013).

At household and community scale, a Canada-supported research programme in Ethiopia's Oromia Region is introducing above-ground plastic digesters linked to small electric generators for individual farms (LIVES Ethiopia, 2015). A newly-built biogas-powered generating unit was also found in Rije village near Abuja, Nigeria, financed with USD 100,000 from the Power Africa Beyond-the-Grid Initiative (Smart Villages, 2016), again at small scale and intended to supply a cluster of households. Both systems use cattle dung.

There is one example from Abuja in Nigeria of **poultry manure** being used in a prospective anaerobic digester system to power a 5 kW motor (Avenam Links, 2017) and two cases in South Africa (Griffiths, 2013) and Botswana (UNDP GEF, 2012) where **pig manure** was to be used, though the current status of these projects is unclear.

A South African poultry manure venture was interesting for its intended use of two 65 kW micro-turbines from Capstone (USA), which can reportedly operate on biogas with methane content as low as 30% (*vs* 60% typically). Although strictly speaking these fall outside the study area scope because they are not traditional internal combustion engines, no lubricants or coolants are required and there is only one moving part, so minimal maintenance is required. These units provide reliable and flexible onsite power generation and produce one-tenth of the carbon dioxide emissions of reciprocating engines with no exhaust after-treatment (Waste360, 2015). Micro-turbines also handle step loads better than gas engines, though they operate at a higher frequency which must be converted to grid frequency using a rectifier and inverter.

There have been a handful of biogas-to-power projects in SSA using **abattoir waste**, of which one (in Burkina Faso) still appears to be generating electricity and provides a productive way to use troublesome waste. This 275 kW_e plant was developed by Fasobiogaz in Ougadougou using Gilbert Brenninkmeyer digester technology and a Waukesha Combined Heat and Power (CHP) generator (Fasobiogaz, 2017). Financed mainly by a Dutch private sector fund, the plant has the capacity to treat 40 tonnes of waste per day and employ 22 people (Jeune Afrique, 2015).

Fasobiogaz biogas plant, Ougadougou

Abattoir waste is also one of the materials feeding a biogas unit at Ashaiman market in Accra, Ghana, which has been developed by the Safi Sana Foundation (Netherlands) to use multiple waste streams from **latrines** and **market stalls**. A 100 kW plant is expected to supply power to 3,000 families (Safi Sana Foundation, 2017).

A larger abattoir biogas project (EUR 500,000) was planned for Dakar, Senegal as a joint venture between Compagnie de l'Eau, de l'Energie et de l'Environnement and Thecogas (Netherlands). A 4,000 m^3 digester was to power a 1 MW generator (seneweb.com, 2014), but the venture is still in its planning stages.

Two biogas-powered electricity systems were also installed with United Nations Industrial Development Organisation (UNIDO) support at abattoirs in the Kenyan capital Nairobi, one at the City Council's Dagoretti Slaughterhouse and the other at Keekonyokie near the Kiserian suburb. The 10 kW_e Dagoretti system was built in 2010, but was non-functional by 2013 due to digester leakage and pump failure (Thomas, 2017). The Keekonyokie 20 kW_e system was intended to power a meat refrigeration unit, but the cooling system was never completed and the gas was instead fed to a mini-grid serving six restaurants. There are reportedly now plans to bottle the gas for commercial distribution (Reuters Global Energy News, 2015).

Municipal by-products

There have been numerous feasibility studies and plans in SSA for anaerobic digestion systems generating heat or power from **municipal by-products**, which include latrine waste, municipal solid waste, sewage slurry and landfill gas. The research team was unable to locate any installation currently functional in the target scale range, however, or indeed which had operated in the recent past.

Agri-residues

The remaining identified examples of anaerobic digestion for combined (cooling), heating and power (C(C)HP) all operate using various forms of **agricultural waste**, including agri-processing, agro-industry, horticulture and floriculture residues. The largest and most successful seem to be in Kenya, where Tropical Power has installed a 2.8 MW system in conjunction with VegPro Group at the 800 ha Gorge Farm in Naivasha which uses **vegetable processing waste** (Tropical Power, 2017). The system was installed in 2015 and includes a biodigester from Snow Leopard, a gas boiler from GE, switchgear and transformers from IET Siemens, instrumentation and control systems from SAR, material handling from BioG and agitators and stirring equipment from Paulmichel. This gives some indication of the sophistication and complexity of state of the art anaerobic digester systems at this scale.

James Finlay Kenya biogas plant, Kericho

Finlays Tea has meanwhile installed a 160 kW_e/170 kW_{th} biogas plant at its Soasa (Kericho) operation using AKUT (German) technology to process mainly **spent tea** (James Finlay Kenya, 2017). The plant can be expanded to 800kW_e. A dual fuel gas-diesel engine runs 23 hours per day and supplies heat for tea drying and power for internal estate use. The co-benefits of avoided waste treatment and provision of high value slurry fertiliser have had a positive impact on the economic case. The system reportedly has a payback period of five years (Douglas-Dufresne, 2017).

Another recent investment in Kenya has been made by the Olivado company on its avocado estate in Murang'a, where a 300 kW biogas system is under construction and will power the factory using **avocado processing waste**. Surplus biogas will fuel the company's vehicle fleet. The plant was supported with a USD 1.3 M loan from the French-funded Chase Bank-SUNREF credit line (SUNREF, 2017).

Siat palm oil waste biogas plant, Makouké, Gabon

Other agri-businesses have invested in anaerobic digestion systems for heat or power at scattered sites across Africa. An example was found in Gabon, where the Belgian-owned Siat Group has built a 1.2 MW plant at its Makouké palm oil estate fuelled with **palm oil mill effluent** to power the company operations and feed surplus to the grid (Gabon Review, 2016).

At Tanzania's Hale Sisal Estate (owned by Katani Ltd.) near Tanga, one of the earliest biogas-to-power systems was installed in 2007 with UNIDO support and runs on **sisal waste** (BioEnergy Berlin, 2016). The twin 150 kW system was still functioning in 2016.

In Côte d'Ivoire, Novis (Germany) developed an innovative containerised biogas plant using **cocoa shells**, though ultimately found it more profitable to convert the shells to food grade cocoa powder for the European market based on bacterial and enzymatic treatment (Helle, 2017).

EEP has supported two South African investors in the development of anaerobic digestion plants. Sucropower and a sugar cane farmer in the Mandini area of KwaZulu-

Natal will process a feedstock of **Napier Grass** and **sugarcane tops and trash** to produce biogas which will be used to generate electricity, fuel and fertilizer (EEP, 2015a). Meanwhile Spring Valley Foods in Bapsfontein (Gauteng) set up a pilot plant to use **fruit processing waste** for biogas-to-power. Neither project is yet thought to be operational (EEP, 2015b).

Lastly, a biogas system in Madagascar fed with **rice husk** appears to have been one of the few installations in Africa with a significant community element (Tribune Madagascar, 2010). The local organisation CASIELEC received French development assistance to set up a facility that would use husk from smallholders and supply power to an unserved community from an 80 kW generator unit.

Summary

In summary, there are a selection of relatively large anaerobic digestion + internal combustion engine installations in Africa, with South Africa and Kenya dominating a field of few players. **Cattle dung** and **agricultural by-products** are the leading feedstocks, usually a by-product of the developer's own core business, and the typical applications are electricity and heat for self-consumption to reduce reliance on costly or unreliable external sources. The sector is small and the early adopters have been larger agribusinesses that control their own feedstock and use the generated energy themselves.

3.2.2 Experience from selected Newly Industrialised Countries

Experiences of anaerobic digestion were investigated for a sample of Newly Industrialised Countries in order to provide a snapshot of adoption and offer provisional insights into the likely challenges and opportunities for transfer to Africa.

India

A range of feedstocks have been tried for biogas in different regions of India, including food waste, cattle dung, municipal solid waste and human waste. Business models that have been tested range from publicly-funded community scale electrification projects (Bowen, 2016) to private enterprises constructing and selling small-scale biogas units (Biotech Renewawable Energy, n.d.) to on-site captive electricity generation by private companies (Clarke Energy, 2014). Operational scale has ranged from 3 kW to 2 MW. While the total number of projects is hard to gauge, a majority of those sampled were found to be in working condition. Various local and international technology providers are active, including Indian companies such as Biotech and international conglomerates such as Clarke Energy, Cummins and the recently closed Entec Biogas. A notable concept is that of Sulabh International, a social enterprise that pioneered biogas generation from public toilets. Their complex in Shirdi (Maharashtra) has 148 WCs and other wash facilities attached to a biodigestion system (Hojnacki, et al., 2011).

The project applies a pay-as-you-use model and is reportedly self-sustaining, courtesy of 30,000-50,000 religious pilgrims each day.

Indonesia

The Government of Indonesia has set a target of 23% renewable energy by 2025, with specific target of 5.4 GW for bioenergy (Conrad & Prasetyaning, 2014). The palm oil, paddy rice and sugar industries account for 80% of all agricultural residues (Ibid.). Unsurprisingly, the largest single feedstock in the identified biogas projects is palm oil mill effluent. Larger plants (1 to 2.5 MW) located very close to the grid seem to be economically viable. These projects are largely financed by the government or through public-private partnerships. The dominant technology providers are a mix of Indonesian firms such as Phoenix Energy and Pasadena Engineering, and international companies such as IUT Global (Singapore), ADI Systems (Asia Pacific) and Ettes Power Machinery (China). One interesting public-private partnership outside the palm oil sector is a government-funded food-to-waste biogas project in Surabaya (Khew, n.d.). Although considered scalable and replicable in other cities, the project suffered delays due to a lack of supportive energy policies.

Malaysia

As in Indonesia, the oil palm sector is Malaysia's largest contributor to biomass production in the form of empty fruit bunches, palm kernel shell, fibres and palm oil mill effluent. Under the Malaysia Economic Transformation Programme, 57 biogas plants have been commissioned within palm oil mills and a further 15 are under development (Kin Mun, 2015), though functionality rates could not be ascertained. The electricity generation potential of such plants is between 1 and 2 MW (Waste Management World, 2012; General Electric, 2016), usually for a combination of grid feed-in and powering in-house facilities and staff quarters. The country's animal husbandry sector is growing rapidly and small scale poultry or cattle dung-based biogas plants have been tested with capacities ranging from a few kW (Nurul Aini, et al., 2012) to 0.5 MW (QL Resources, n.d.). In addition to international groups such as Camco, Veolia and Cummins, local project developers have emerged over the past 6-7 years such as Cenergi, Green Lagoon Technology, Biogas Environmental Engineering and Biotech International Asia.

Thailand

Over the past decade, Thailand's biogas industry has expanded rapidly and had reached an installed capacity of 311 MW by September 2014. This included support via the Energy Conservation ('enCon') programme for the development of biogas plants on medium to large farms, particularly pig farms (GIZ, 2014). In the early 2000s, government support expanded to other agro-industrial installations such as cassava starch mills, part of a key Thai export industry, followed by palm oil mills (Centre for

Clean Air Policy, 2012). Power output in these industrial settings ranges from 500 kW to 3 MW. More recently there has been political support for biogas from energy crops such as Napier Grass (Alensys, n.d.) and municipal waste (3R Knowledge Hub, 2014). Notable technology providers include Waste Solutions (New Zealand) and GE (Jenbacher) engines, with distribution and service partners such as Italthai Industrial, MK Protech and ICLEI handling system operations. A milestone project was the Khorat Waste to Energy project in Sanguan Wongse Industries. This was the first fully commercially-financed biogas project in Thailand and used the Build-Own-Operate-Transfer ('BOOT') model, with Sanguan Wongse eventually taking ownership. This model represented a significant turnaround for the industrial biogas sector, prompting the development of similar BOOT projects in which mill owners invested their own capital and local banks provided debt financing.

Philippines

Unlike some of its S/SE Asian counterparts, the Philippines has recorded limited progress in the development of anaerobic digestion. The Department of Environment and Natural Resources has been promoting biogas production in large pig farms, however, especially those already equipped with waste lagoons. Three such projects were identified in Quezon City (Bioenergy Insight, 2014), Cavite Pig City (Entec, n.d.) and San Miguel's Sumilao Piggery Complex (Solutions Using Renewable Energy, n.d.), with large power generating capacities of 6 MW, 1.1 MW and 0.4 MW. Another significant project is based on municipal by-products such as latrine waste and septic sludge. Given the fledgling state of the industry in the Philippines, the technology developers are so far mostly European firms such as Entec and Envitec Biogas. Local interest is growing, however, with companies such as SURE and Aseagas partnering with Biodome Asia and GE to take up biogas opportunities (Aseagas, 2015).

Brazil

The commercial biogas sector in Brazil contributes about 80 MW of power to the electricity grid, a small fraction of the total renewable energy production (IEA, 2014) because hydro power is generally a cheaper option. According to the IEA, there were 22 biogas plants connected to the grid in 2014, a majority of which use agricultural, livestock and municipal waste as feedstock. Pig manure has been particularly interesting given its availability in large quantities, since Brazil produces 3.3 million t/yr of pork meat. Two case studies identified using pig manure were a public-private partnership project implemented by Sadia, a frozen foods company, and a Clean Development Mechanism project implemented by AgCert, a biodigester development company (Hojnacki, et al., 2011). There are an increasing number of households in Brazil with sanitation and garbage removal services and this is creating an opportunity for biogas production from wastewater treatment and landfill gas (Medeiros, n.d.). A notable example of a cooperative-owned biogas plant was developed by the ITAIPU Binacional Renewable Energy Platform in 2009. The project consists of 33 family farms with 400 cows and 5,000 hogs. Each participating property has a digester, producing a combined gas total of 570 m^3/day, which is carried by 25 km of piping to a 100 kVA generator. The gas is used to generate heat and electricity, and to operate grain dryers.

Summary

Rapid growth of anaerobic digestion can be seen in several Newly Industrialised Countries, with a good degree of commercial success. Policy factors such as renewables targets, tax-incentives, Feed-in Tariffs and government subsidies can play an important catalytic role, as seen in Thailand.

The highest success rates are seen in medium- to large-scale biogas plants (500 kW to 3 MW), mainly operated by agro-processing industries. They seem to have enjoyed easier access to loans and commercial finance; security of feedstock supply from their own sources; incentives such as Certified Emission Reductions and Power Purchase Agreements; and contractually binding arrangements with technology providers for maintenance and repair.

There have been more challenges in rolling out anaerobic digestion at the smaller scale of 1 to 500 kW in communities and on farms. The main barriers seem to be: (i) lack of investment capital and access to commercial finance; (ii) lack of commercial project developers interested in smaller projects due to lower margins; (iii) unreliability of feedstock supply; (iv) low equipment quality with inadequate support and warranties; and (v) convenience and low cost of alternative fuels.

Anaerobic digestion demonstrates good transferability potential to Africa and there are promising indications around the benefits of the technology (such as feedstock flexibility and scalability), but also pitfalls such as the likely need for financial incentives to kick-start investment, especially for small-scale projects that developers may find less attractive.

3.2.3 Opportunities for BSEAA

Potential for innovation

There are indications that anaerobic digestion may offer a number of innovation opportunities for SSA in both the technology and the application of the energy.

For example:

- The South African company **Selectra** has designed a prototype 'Dairy Power Box' that can produce 70 kW_e + 15 kW_{th} (Selectra, 2014). This potentially provides a self-contained, portable heat and power solution for cattle farms and dairies, with easy installation and minimum disruption to ongoing operations. The system has been trialled in Botswana with a EUR 180,000 EEP grant (Wiemann, et al., 2015).
- The Mexican company **Sistema Biobolsa**, a specialist in flexi-bag biogas solutions, has recently opened a branch in Kenya with DFID support (via the Shell Foundation). The company creates thermal, mechanical and electrical energy from 2 to 15 kW and has also worked on direct thermal cooling (Eaton, 2017). They now wish to explore localisation of their technology for the African context.

Sistema Biobolsa installation in Mexico

- SNV with **Simgas** (Netherlands) are piloting a biogas-powered milk chiller with 10 litre capacity for farm-level use in Kenya, Tanzania and Rwanda, which has the potential to improve the income of small dairy farmers, help supply to meet demand, help farmers to access the formal dairy market and contribute to improved nutrition (SimGas, 2017). Although this system does not employ an internal combustion engine, it may still be of interest if scaleable for use at dairies.
- Simplified **control systems** are needed to suit the requirements of small-scale anaerobic digesters, as systems designed for European installations tend to be overly sophisticated (Boshoff, 2017). There may be an opportunity to develop lower-tech ancillary equipment for controlling heat or power production systems that are better suited to small size digesters.
- Existing project developers in South Africa and Kenya may be keen to explore **novel African feedstocks**, specific to the countries where they operate. The early developers of these technologies are often likely to make the best partners for replication and scale-up (Franz, 2017).

'Pro-poor' potential

There are so far almost no examples of anaerobic digestion for C(C)HP being applied in smallholder agriculture or other community-based settings in SSA, and this may represent an opportunity for achieving greater development impact if the concept can be sufficiently de-risked. Although the operation and maintenance of modern anaerobic digestion systems for C(C)HP is not a straightforward matter by any means, biogas technology has a number of inherent features that make it potentially interesting outside sophisticated industrial environments. For example:

- The production of biogas is a relatively passive process, provided that sufficient and appropriate feedstock is supplied; the system does not require continuous feeding and tending.
- The biofuel (in the form of gas) may be stored within the digester and consumed when needed, implying some flexibility when matching fuel supply with energy demand.
- Although the gas has relatively low calorific value, engine start-up time is minimal so the energy is 'dispatchible' (i.e. can be provided on demand).
- Feedstock flexibility is high, potentially facilitating replication across a variety of environments or across several feedstocks at a single installation.
- Various pro-community supply models can be envisaged in which multiple feedstock providers would provide raw material to a central digester.
- Biodigester technology is down-scaleable to suit relatively small installations, with gas or dual-fuel engines similarly available in a range of sizes.
- Improvements in the durability of synthetic materials are driving the development of cheaper, on-surface digester units that are more affordable and flexible for smaller-scale users.
- The digestate has value as organic fertilizer, for own use or onward sale.

Despite these advantages of biogas as a technology option, connecting the gas output to C(C)HP systems still presents significant practical challenges that should not be under-estimated if a 'pro-poor' orientation is sought.

Prospects for DFID additionality

SSA so far represents a relatively small market for developers of anaerobic digester projects for C(C)HP. Compounded by the risks of doing business on the continent and the absence of renewable energy subsidies that might be offered to investors in (e.g.) European countries, this means that the transfer into SSA of modern anaerobic digester technology has so far been limited outside South Africa. There are nevertheless indications (for example from the two recent installations in Kenya) are that early adopters in the dairy, tea, floriculture and horticulture sectors are now seeing opportunities to adopt this technology, which is fully commercially developed in other regions of the world. There may be a useful role for DFID in addressing barriers to scale-up by supporting targeted research, and to add momentum to the growing interest in commercial biogas in Africa.

Replication potential

Human and animal wastes clearly offer great potential for anaerobic digestion, and the range of feedstock options within these categories will be retained for further investigation in the case study phase.

Among the agricultural and agro-industrial by-products also identified as potential feedstocks, it is proposed that case study research should only proceed for those that are potentially available in at least half of the ten countries that were shortlisted in the previous study phase, to ensure a minimum level of replication potential. Table 3 lists the crops from which the various feedstocks are generated as by-products, and indicates in which of the DFID shortlisted countries they are grown. Green indicates availability while red indicates poor/no availability

Table 3. Existence of commercial crop cultivation in priority countries (FAO, 2017)

Prioritised countries	Avocado	Sugarcane	Cocoa	Maize	Oil palm	Potato	Rice	Sisal	Sunflower	Tea
Ethiopia	Green	Green	Red	Green	Red	Green	Green	Green	Red	Green
Ghana	Green	Green	Green	Green	Green	Red	Green	Red	Red	Red
Kenya	Green	Green	Red	Green	Red	Green	Green	Green	Green	Green
Mozambique	Red	Green	Red	Green	Red	Green	Green	Green	Green	Green
Nigeria	Red	Green	Green	Green	Green	Green	Green	Red	Red	Red
Rwanda	Green	Green	Red	Green	Red	Green	Green	Red	Red	Green
Tanzania	Red	Green	Green	Green	Green	Green	Green	Green	Green	Green
Uganda	Red	Green	Green	Green	Red	Green	Green	Green	Green	Green
South Africa	Green	Green	Red	Green	Red	Green	Green	Green	Green	Green
Zambia	Red	Green	Red	Green	Red	Green	Green	Red	Green	Green

As Table 5 shows, all of the agro-based feedstocks except cocoa and oil palm are available in at least half of the prioritised DFID focal countries. The case study phase will therefore omit these two feedstocks, but will explore anaerobic digestion TVCs examples that use the other options as follows:

a) Animal by-products, including **cattle dung**, **pig manure** and **poultry manure**;

b) Municipal by-products, including **municipal solid waste**, **sewage sludge and**, **human waste**;

c) Agricultural by-products, including **fruits wastes** (e.g. avocado), **bagasse**, **maize cobs and stalks, potato waste, rice husk, sisal waste, sunflower waste** and **tea waste.**

3.2.4 Summary and implications

Anaerobic digestion is a well-developed technology that has been widely adopted globally for the production of C(C)HP. Accelerating uptake can be anticipated in SSA, based on early adoption by livestock and agri-businesses in South Africa and Kenya. There are areas of innovation potential (as mentioned) where research could have a role to play. Provisionally these seem to be around the development of cheaper and more durable materials for digesters, direct cooling applications (especially in the dairy industry), lower-cost control systems for small-scale heat and power production, and potential expansion to Africa-specific feedstocks. The timing is right to support this developing sector, with an opportunity for DFID to provide targeted research assistance to address specific bottlenecks.

The most promising feedstock opportunities seem to lie in municipal by-products, animal wastes and the by-products of agricultural processing, especially fruit and vegetable processing residues. A selection of specific crop feedstocks has been proposed, based on replication potential in at least half of the shortlisted focal countries. The greatest challenge for DFID may lie in finding business models that are pro-poor but can at the same time be realistically managed within the capacity of mid-sized farms, industries and local communities.

3.3 Gasification

3.3.1 TVC descriptions

Project overview and status

The second shortlisted technology combination for TVC identification was **gasification plus internal combustion engine**, with the syngas feeding a gas or dual-fuel engine to deliver heat, power or cooling services. 47 such examples were identified in SSA and their status is summarised in Table 4.

Table 4. Biomass gasification projects identified in SSA <5 MW

Status	No.
Feasibility study	7
Operational	7
Under construction	1
Planned	6
Abandoned/shut down	12
University research pilot	2
Status unclear	12
Total	**47**

As the table shows, there are seven gasification feasibility studies yet to be followed through, including one for a sizeable 4 x 1 MW installation in Benin (UNDP, 2016). Six ventures are still being planned while the others have either been abandoned or stopped operating (12), represent academic pilot tests (2) or their current status is unclear (12).

Among the projects that have reached implementation stage, no more than eight are believed to be operational or are under construction (including one still in pre-testing) and these are demonstrations rather than commercial ventures. Four of the gasifiers - two in Uganda from Husk Power Systems, one in Benin from All Power Labs and one in Nigeria from Ankur Scientific - operate only intermittently. A gasifier in Nigeria from the Indian Institute of Science required an Indian engineer to come in for essential repairs, while two All Power Labs gasifiers in Ghana have only been operating for a month (Ertl, 2017; Thomas, 2017; Owusu-Takyi, 2017). No gasifier could be identified in SSA that has operated successfully over several years at a high capacity factor (>80%).

Energy output range

The majority of the biomass gasification projects in SSA are below 100 kW_e (see Figure 3) and have been installed at community level or in small-scale productive settings. Unlike anaerobic digestion, larger projects of 100 kW_e to 1 MW_e are rarer and typically found in medium-to-large scale agricultural or wood processing operations. Above 1 MW_e, there are just four projects, one in the initial testing phase and three with unclear status. The great majority (>80%) for which an energy application could be identified produce only electricity.

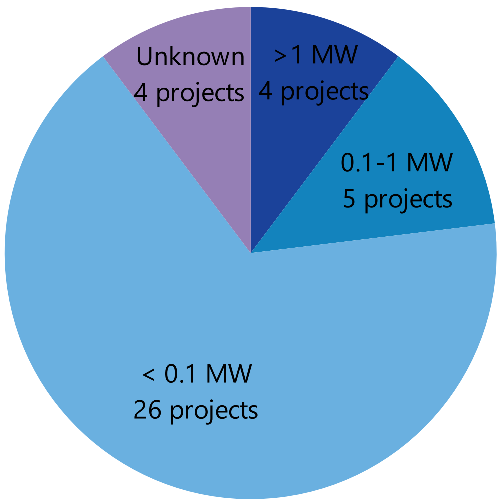

Figure 3. Scale range of gasification TVC examples (excluding research pilots and feasibility studies)

TVC profiles

The TVCs identified for gasification are summarised in Figure 4.

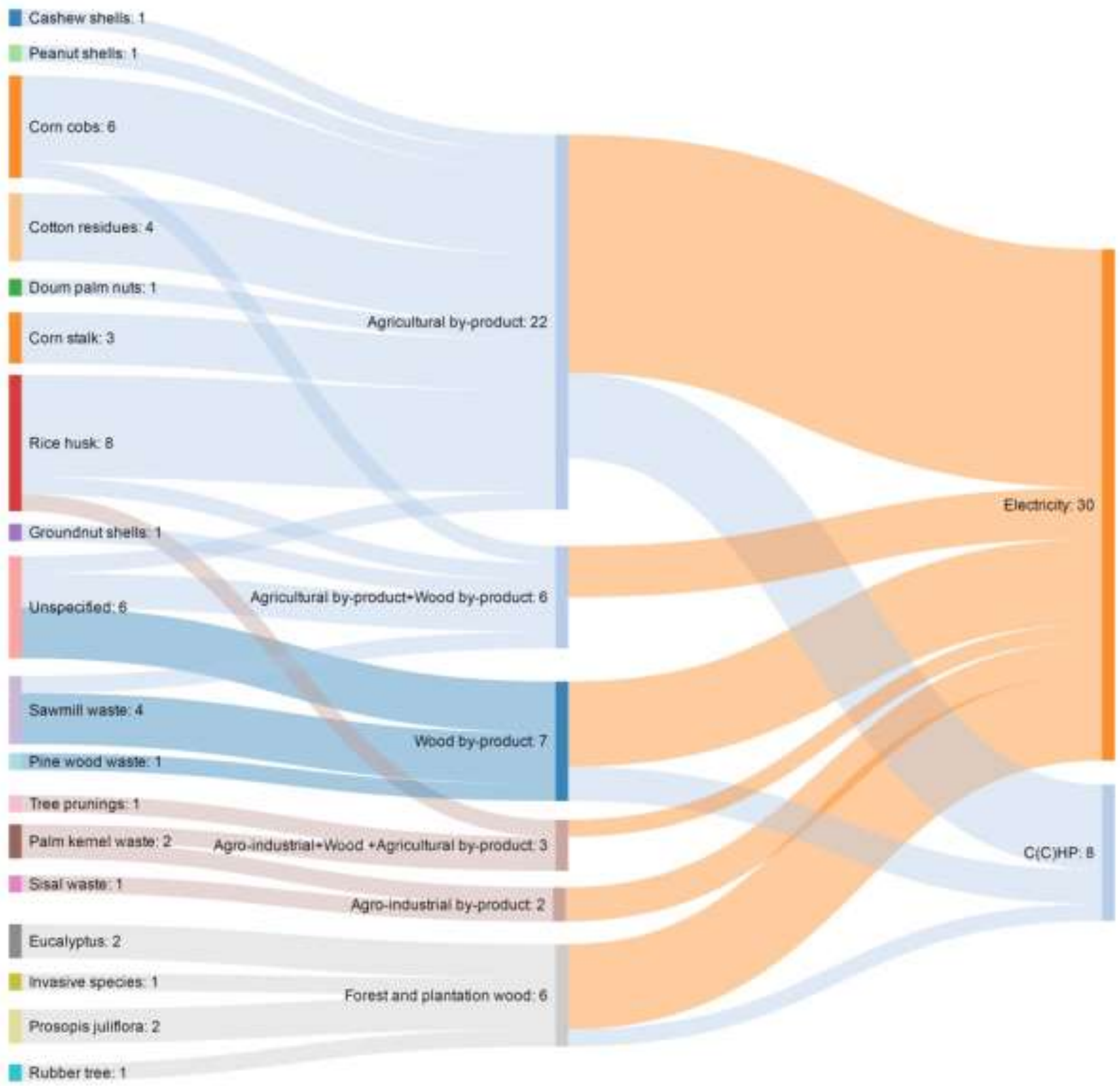

Figure 4. TVC profiles for gasification + internal combustion engine

Feedstock overview

Excluding feasibility studies and research pilots, around 60% of the identified projects use agricultural or agro-industrial by-products as feedstock, while the remainder use woody by-products or forest/plantation wood. All four of the projects above 1 MW_e rely on woody biomass, either wood chips from forestry processing waste or thinnings. Woody residues are the dominant feedstock globally for gasification so it is unsurprising to see the same pattern reflected in the larger African examples.

Agricultural by-products

Of the 18 TVC examples that use agricultural by-products, just three are operational and employ gasifier technology from Husk Power Systems (India). These include two installed by Pamoja Cleantech in Tiribogo and Sekanyoni villages in central Uganda, both fuelled with **maize cobs** and other agricultural by-products to feed local mini-grids (Pamoja Cleantech, n.d.). These systems, both thought to be part-financed by Energy4Impact, are reportedly working intermittently and cannot be considered economically sustainable (Ertl, 2017). The largest operating gasifier using **rice husk** (500 kW_e) is at Kilombero Plantations in Tanzania and has received equity finance from AgDevCo (AgDevCo, n.d.). Due to tar cleaning problems the plant operated only intermittently at first, but is now reportedly functioning again (James, 2017).

Four projects in the planning stages also intend to use agricultural residues**:**

- A further Pamoja Cleantech project in Uganda (Kamwenge District) will use **maize cobs and rice husk**. This 50 kW_e installation, part-financed by EEP, is currently sourcing technology providers and will include a dry filtration system for the gas and a CHP unit producing at least 100 kW_{th} for a biomass dryer (Pamoja Cleantech, 2017). The gasifier will operate in parallel to a 50 kW inverter connected to a 120 kWh battery bank.
- A 32 kW_e project in Tanzania using **rice husk**, developed by Ageco Energy & Construction, a local Engineering, Procurement, and Construction (EPC) company (Coogan, 2017).
- A 75 kW_e gasification project in a cashew-producing area of Tanzania with unreliable grid supply, supported in part by UNIDO (Thomas, 2017). This project intends to use **cashew shells** from local farmers as feedstock.
- A EUR 1.75 million project in Mozambique (co-financed by Energias de Portugal, the cotton company Sociedade Algodoeira do Niassa, João Ferreira dos Santos, the government of Mozambique, EEP and the OPEC[4] Fund for International Development) is planned, but currently on hold due to licensing difficulties (Marques, 2017). It intends to supply a hybrid mini-grid alongside solar PV and diesel as backup (EEP, 2015c). Local farmers were to benefit from sale of **cotton residues** and access to electricity (UNDP, 2015). The project will use a 15 kW_e All Power Labs gasifier and has bought three additional back-up units, given the lack of local engineering support (Marques, 2017).

[4] Organization of the Petroleum Exporting Countries

A relatively high proportion of projects using rice husk is perhaps surprising, given the difficulty that high ash content reportedly presents for this material (Sharan, 2017).

Eight projects that are either abandoned, shut down or not operational also use(d) agricultural residues:

- Five west African ventures were developed by Novis in the 11-70 kW_e range, none of them now functioning due mainly to a lack of suitably skilled operators (Helle, 2017). They included:
    - Two units of 11 and 35 kW_e in Benin and a 35 kW_e unit in Burkina Faso, all using **maize and cotton stalks** and gasifiers from Ankur Scientific (India). Both units in Benin were set-up for CHP, the operators were trained by Ankur and a Togolese engineer was responsible for maintenance and repair. This still proved insufficient to overcome the technical challenges of the gasifier, which included clogging of the valves and a requirement for precise management due to a low degree of automation (Helle, 2017). The installation in Burkina Faso was financed by the German carbon project developer Atmosfair, and was to provide electricity to a hospital. It reportedly stopped operating because the complexity of operation exceeded the capacity of the local technicians (Ibid.).
    - Two units for CHP in Senegal, also developed by Novis, one of 32 kW_e using **stalks, sorghum waste and peanut shells** and the other of70 kW_e using **rice husk** (Ibid.). At the smaller unit, financed by Deutsche Investitions- und Entwicklungsgesellschaft (DEG) and Stadtwerke Mainz, peanut shells were pelletised to improve the mass flow of the gasifier. Unlike the other Novis projects that failed for technical and maintenance reasons, in this case the company's own engineer operated the plant, but the business model was apparently not viable as the population could not afford to pay for the energy (Helle, 2017). At the larger Senegalese unit, the operations staff received three months' training from Ankur, but then left the company so the skills were lost.
- Ruaha Power (an affiliate of Continental Energy) and Husk Power Systems set up a biomass gasification-diesel mini-grid in Morogoro Region of Tanzania (PRNewswire, 2014; Jonker-Klunne, 2017). The project uses **unspecified agricultural residues** and is part-financed by the EEP programme, but is currently not operational (EEP, 2015d; Sinha, 2017).
- Pamoja Cleantech installed an All Power Labs gasifier near Gulu in Uganda with the support of the World Bank and UNIDO, using **maize cobs and other agricultural residues**. The gasifier ran for only 300 hours for lack of technical engineers and could not be maintained locally (Ertl, 2017). A second All Power Labs unit reportedly operated for less than an hour after arriving in Uganda (Ibid.).

- All Power Labs installed a 10 kW_e unit at Turkana Basin Institute in Kenya using **doum palm nuts** which is not operating anymore given the technical complexity of the All Power Labs unit, the high degree of automation and limited possibilities for local repair requiring in-depth engineering knowledge (Leakey, 2017).

The status of three projects using **maize cobs and rice husk** is currently unclear. These include two (co-)financed by EEP in Tanzania. The examples in Tanzania were intended to provide electricity to households, SMEs and trading centres. The third agri-residue project with an unclear status is in Chad and uses an All Power Labs gasifier of 18 kW_e rating and was installed in 2013 (All Power Labs, 2013).

Agro-industrial by-products

As previously stated, agro-industrial by-products are defined as residues from non-staple food industries, as distinct from the by-products of processing basic food crops.

The two identified TVC examples using such feedstocks include a new 20 kW_e All Power Labs gasifier that has operated only since February 2017 at the Kumasi Institute of Tropical Agriculture in Ghana using **palm kernel shells,** and a gasifier using **sisal waste** at the Rea Vipingo estate in Kenya (Practical Action, 2012). The Ghana project was financed by the Power Africa Off Grid Challenge and is struggling to find a reliable operator and faces maintenance difficulties and uncertain economic viability (Kumasi Institute of Tropical Agriculture, 2016; Owusu-Takyi, 2017). The status of the sisal estate operation in Kenya is unclear, pending ongoing enquiries by the team.

Mixed feedstocks

Two projects use or intend to use a mix of agricultural, agro-industrial and wood by-products. A 32 kW All Power Labs gasifier at the Songhai NGO Centre in Benin uses a mix of **tree prunings**, **rice husk** and **palm kernel cake** (All Power Labs, 2015). Other gasifiers have possibly been tested at the same site, subject to confirmation during the case study phase. A 120 kW_e Ankur gasifier is reportedly being developed in Mkuranga District, Tanzania by Space Engineering Company using **agricultural waste and forestry residue**. The project is to be financed by the Daey Ouwens Fund for Small Scale Renewable Energy Projects (Daey Ouwens Fund, 2011).

Forest and plantation wood

This category refers to woody biomass harvested directly for use as fuel, as opposed to a by-product of wood processing. The only operating project using forest or plantation wood directly is a 32 kW_e gasifier in Nigeria fired by **wood-chips** that provides electricity to productive users such as rice and flour mills. UNIDO cooperated with Ebony Agro Industry and the state government on this project, which is run by a specifically established cooperative and financed by the South-South Cooperation of India (Thomas, 2017).

Six other projects also use forest or plantation wood as feedstock, but are either under construction, shut down or have unclear status.

These include the largest gasification project in SSA, the 2.4 MW_e Tower Power venture at Marigat in Kenya, which will use Cummins Power equipment fuelled with wood chips from invasive ***Prosopis juliflora***. The project is in the last phase of testing to overcome gas cleaning challenges as the cyclone, scrubbers and water supply were reportedly under-spec for the tar load and have had to be upgraded (confidential commercial source). The raw material will be supplied by community-based organisations from grazing areas taken over by the thorny, invasive prosopis tree. The same investor hopes to develop other gasification opportunities in East Africa if the gas cleaning challenges at Marigat can solved.

Three projects that used wood waste have now been decommissioned, one 180 kW_e unit at a tea estate in Uganda using **eucalyptus blocks,** a 250 kW_e gasifier in Namibia using **invader bush** and a 10 kW_e Ankur gasifier in Uganda using **eucalyptus prunings** (Buchholz, et al., 2012; Baker, et al., 2011).

The Ankur gasifier at James Finlay's Muzizi tea estate in Uganda worked successfully from 2006-2009 after a local engineer was trained for 3 months in India, but encountered technical problems related to load changes and resulting drop in frequency (Douglas-Dufresne, 2017). The project was decommissioned after the tea estate became connected to the grid.

Decommissioned Ankur gasifier and filter line, Muzizi tea estate, James Finlay Uganda

The Namibia project negotiated a Power Purchase Agreement with the NamPower utility, but the plant faced technical problems. The significant water requirements in a water-scarce country led to the eventual shutdown of the project (Bosch, 2010).

A small 10 kW gasifier in Uganda, financed by German Development Service (DED), was decommissioned after the host farmer relocated and it was transferred to the Makerere University campus (Buchholz, et al., 2012).

The status of two gasifier projects that use rubber trees (*Hevea brasiliensis*) and *Prosopis juliflora* as feedstock are unknown. The former is an 18 kW_e All Power Labs gasifier at BWI's Renewable Energy Centre in Kakata, Liberia and the latter was developed by the Ethiopian Rural Energy Development and Promotion Centre (All Power Labs, 2017a; Energypedia, 2015b).

Wood processing by-products

Seven gasification projects using by-products from wood processing were identified in SSA. One is planned, one has shut down and the status of the other five is unclear:

- Pamoja Cleantech is planning a **wood waste pellet** gasification project in Uganda using more sophisticated German gasification technology from Entrade (Ertl, 2017). The container-based unit has a capacity of 2 x 25 kW_e and 2 x 60 kW_{th} at an efficiency of 85%, promising 8,000 operational hours per year (Entrade, 2017).
- A 50 kW_e gasifier at the Nyabyeya Forestry College in Uganda used **sawmill wood offcuts**, but is reportedly no longer working (Ertl, 2017; Wambi, 2016).
- The five gasification projects with unclear operational status are:
    - An All Power Labs 18 kW_e gasifier at Chelinda Lodge in Malawi using **waste pine wood** (All Power Labs, 2017b).
    - A 1 MW_e (2 x 500 kW_e) gasifier in Kaputa, Zambia, part of an isolated mini-grids project executed by UNIDO with the Global Environmental Facility, the United Nations Environment Programme (UNEP), the Zambia Electricity Supply Corporation, the Development Bank of Zambia, the Rural Electrification Authority and the International Centre on Small Hydro Power (China) (UNIDO, n.d.).
    - A 1 MW_e plant from Chinese firm Fengyu Corporation at an undisclosed site in Kenya, believed to be using **sawmill waste** (Fengyu Corporation, 2013; Makepolo, n.d.).
    - Two projects in South Africa, one developed by Recor International using a 25 kW_e gasifier and another apparently using a gasifier from Black Swan Group (Recor International, 2013).

Unspecified feedstock

Two gasification projects use an unspecified feedstock. These include one using an All Power Labs gasifiers in Tamala, Ghana, which was installed in February 2017 (Owusu-Takyi, 2017) and a second by Carbo Consult & Engineering in South Africa. Despite winning a Frost & Sullivan design award for developing a tar-free biomass gasification systems, the current status of this project is unclear (Burger, 2017).

3.3.2 Experience from selected Newly Industrialised Countries

A brief overview of gasification experiences in other developing regions of the world can indicate the scale of adoption and offer provisional insights into the potential challenges and opportunities for transfer to Africa.

India

India has several developers of small-scale gasifier technology including Ankur Scientific, DESI Power, Husk Power Systems, Saran Renewable Energy and The Energy and Resources Institute (TERI) (Bhattacharyya, 2014; TERI, 2017), which between them have installed at least 400 small-scale units (Husk Power Systems, 2017; DESI Power, 2017; Practical Action Consulting, 2012)[5]. They typically operate in the 10 kW to 1 MW range, run on agricultural residues, weeds or wood waste, and have usually received government funding. A number of plants are closed or have yet to be commissioned due to technical issues (Ravindranath, et al., 2004). One of the largest developers of community-based mini-grids in India reports only five gasifiers still working out of more than 40 installed, due to technical challenges and insufficient demand for the electricity at the available times and costs (project developer interviewed in confidence). A study in India by the United Nations Development Programme concluded that further improvements to gasification technology related to syngas impurities, water consumption and wastewater treatment were still required to increase operational reliability (UNDP, 2013).

Indonesia

In Indonesia there is limited use of biomass for power production as it is a more expensive option than fossil fuels (Sugiyono & Nurrohim, 2007; Sriwannawit, et al., 2016). This contrasts with the findings of a 1980s assessment when small-scale gasifiers were apparently widely disseminated - although performance needed to be verified (Grassi, et al., 1992). The study noted that the gasifiers had operated satisfactorily from a technical point of view, notwithstanding high tar content in the gas (Ibid.), but in economic terms they had performed poorly due to high capital costs, competition from fossil fuels and poor reliability (Grassi, et al., 1992; Stassen, 1995). Unreliability was attributed to inadequate technical support and training of operators (Grassi, et al., 1992). In common with India, the mass adoption of small-size gasifiers does not seem to have led to the durable and sustainable development of this technology in Indonesia. A small number of contemporary sub-1 MW gasification plants were found, fuelled with rice husk or wood waste to provide electricity or CHP (Rasmussen, 2011; Pasadena Engineering, 2014; Biomass Magazine, 2014). The country is a major palm oil producer and there could be potential for using palm empty fruit bunches as gasifier feedstock (Pradana & Budiman, 2015).

Philippines

The first biomass gasifier in the Philippines was commissioned in 2012 in Dinalungan (Bioenergy Insight, 2012). Owned and operated by Eco Market Solutions, the plant has

[5] Excluding gasifiers from Ankur Scientific, for which data are not publicly available.

a capacity of 250 kW and uses wood waste, agricultural waste and coconut residues (Rasmussen, 2012). The National Power Corporation has an agreement with Clenergen Corporation to install over 50 small-scale (2 MW) biomass gasification plants across the country (Clenergen Corporation, 2010; Biomass Magazine, undated), though the current status is not clear.

Thailand

Several small-scale biomass gasification plants have been installed in industrial operations in Thailand for demonstration or research purposes since 2005, most with government subsidy (Salam, et al., 2010). Various feedstocks have been tried, including rice husk, wood waste, agricultural residues (such as maize cobs) and oil palm empty fruit bunches (Salam, et al., 2010; Laohalidanonda, et al., 2015; Thomas, 2017). Technical barriers (such as high tar content) and non-technical barriers (such as high cost and unreliable feedstock supply) have hampered commercial operation. In fact almost all of the gasification plants for electricity generation have failed after a short period of operation (Salam, et al., 2010). Policy-related issues also reportedly halted the progress of a planned 250 kW gasification project based on bamboo waste (Thomas, 2017).

Brazil

Biomass gasification is an expensive energy option in Brazil compared to using bagasse in CHP plants, and is yet to reach market maturity (Simon, et al., 2016). There has been little commitment shown for this source of renewable energy (Santos, 2013). Very few patents for biomass gasification plants have been filed by Brazilian technology developers and projects rely on imported technology (Ibid.). One pilot gasification project was identified at the sub-1 MW scale, using wood waste as feedstock (Coelho, et al., 2006). The technology was imported from the Indian Institute of Science and the project aims to link community development with renewable energy production (International Energy Initiative, 2003). Challenges that were faced included high operation and maintenance costs, insufficient technical capacity of operators and difficulties with gas cleaning and waste water handling (Ibid.).

Summary

Small-scale biomass gasification has been introduced at a range of scales in India, Thailand, Indonesia, the Philippines and Brazil, often with the support of national governments and international development agencies. Gasification linked to commercial operations such as rice mills, coconut farms or wood processing enterprises has in theory offered a model that ensures reliable supply of feedstock and an anchor load for the power generated, with the potential for selling surplus to the grid (Bhattacharyya, 2014; Sharan, 2017). However, projects have encountered challenges related to consistency of feedstock supply and technical issues such as impurities in the syngas, high demand for water and discharge of that water once contaminated (Thomas, 2017). A lack of suitably skilled operators has also been a reason for failure. High capital costs have meanwhile impacted economic viability, which can be addressed in part by using locally fabricated gasifiers that can be maintained by operators with limited technical expertise (Bhattacharyya, 2014). While India has led the way in small-scale gasification and offers transferability lessons for Africa, government subsidy is thought to have been a significant enabling factor. There is also limited evidence of long-term operation at community level.

3.3.3 Opportunities for BSEAA

Potential for innovation

Only 47 biomass gasification projects were identified in SSA and no more than seven are currently believed to be (intermittently) operational. The considerable numbers of failed, struggling or unclear projects present areas for innovation in order to increase operational reliability and to create economically viable business models. The next phase of this assignment requires more detailed analysis of the reasons for past and current failure. Potential opportunities include:

- Technology simplification to overcome the lack of engineering skills for local operation and maintenance (Helle, 2017; Sharan, 2017).
- Wider application of C(C)HP, not just power generation, to pre-dry biomass and meet local heating and cooling demands.
- Improved gas cleaning and ash handling systems for the cheaper and simpler gasifier systems (Sharan, 2017).
- Better wastewater treatment systems from the wet gas cleaning process, or the option to change to dry gas cleaning systems to reduce costs and avoid wastewater issues.
- Development of closed-loop water systems for gas cleaning in order to reduce overall water requirements (Thomas, 2017).

- Development of local and regional engineering education and training capacity.
- Provision for gas storage to allow more flexible operation of the engine in response to changing loads (Douglas-Dufresne, 2017).
- Development of gasifiers that can accept a wider variety of feedstocks.
- Increasing the value of biochar for water purification or as fertilizer.
- Developing business models with greater developmental impacts.

Potential innovation opportunities such as these could be investigated further during the next phase to evaluate whether they are genuine opportunities, whether they are being addressed already and what value DFID research funding could add.

'Pro-poor' potential

The majority of gasification projects in SSA are small-scale (<100 kW_e) and located in community settings or small-scale agro- or forest industry. The pro-poor impact is potentially high for feedstock supply or provision of electricity (and potentially heat or cooling) in off-grid areas. As the analysis has shown, however, only a few such projects are operational and even these tend to function intermittently. Unless the reliability of smaller-scale gasification projects can be improved, pro-poor impact will be limited because the systems simply won't keep working.

Larger gasifier operations are meanwhile more likely to use their own self-managed feedstock (typically woody biomass) and to consume a majority of the energy on site. They create jobs, export electricity and deliver higher level benefits to local and national economies.

Finding the 'sweet spot' between small-scale projects that are frequently unsustainable and large-scale industrial ventures that potentially have fewer pro-poor benefits is a challenge that needs to be considered.

Prospects for DFID additionality

Gasification has been adopted at scale in Asia, particular in India, whereas operational projects in SSA are still very rare. Technology providers (such as Husk Power Systems) and project developers (such as Pamoja Cleantech) now have a permanent presence in Africa and are actively developing pilot projects, but have yet to introduce a successful combination of technology and business model. All small-scale gasification projects in SSA have been donor-funded. DFID support could potentially unlock opportunities in technology, business models and supply chain innovations, filling a gap left by other developments agencies that focus on direct operational investments.

Replication potential

Woody feedstocks offer high potential for gasification, based on global experiences with this technology, and will be retained for further investigation in the case study phase.

Among the agricultural and agro-industrial by-products also identified as potential feedstocks, case study research will only proceed for those that are potentially available in at least half of the ten countries that were shortlisted in the previous phase of this assignment, to ensure a minimum level of replication potential. Table 5 lists the crops that generate these by-products and indicates in which of the shortlisted countries they are grown. Green indicates availability while red indicates poor/no availability

Table 5. Existence of crop cultivation in priority countries (FAO, 2017)

Prioritised countries	Cashew	Cotton	Groundnut	Maize	Oil palm	Rice	Sorghum	Sunflower
Ethiopia	Red	Green	Green	Green	Red	Green	Green	Red
Ghana	Green	Green	Green	Green	Green	Green	Green	Red
Kenya	Green	Green	Green	Green	Red	Green	Green	Green
Mozambique	Green	Green	Green	Green	Red	Green	Green	Green
Nigeria	Green	Green	Green	Green	Green	Green	Green	Red
Rwanda	Red	Red	Green	Green	Red	Green	Green	Red
Tanzania	Green	Green	Green	Green	Green	Green	Green	Green
Uganda	Red	Green	Green	Green	Red	Green	Green	Green
South Africa	Red	Green	Green	Green	Red	Green	Green	Green
Zambia	Red	Green	Green	Green	Red	Green	Green	Green

As the table indicates, all feedstocks except oil palm are grown in at last half of the ten prioritised DFID countries. The case study phase will therefore look for gasification examples that use:

a) Wood and wood processing by-products, including **logs, sawdust, wood chips, pellets** and **offcuts;** and

b) Agricultural by-products, including **cashew shells, cotton stalks, groundnut shells, maize cobs and stalks, rice husk** and **sorghum stalks.**

3.3.4 Summary and implications

Small-scale gasification below 100 kW_e represents one of the only technologies capable of producing electricity from agricultural by-products at a reasonable level of efficiency. Although small- to medium-scale gasification is a technology that has been applied widely in South Asia, , results have been mixed and the team could not identify any gasification projects in SSA that have been operating reliably over a period of years. Reliability is hampered by lack of technical capacity, stringent feedstock requirements, high tar content of the syngas and contamination of cleaning water.

None of the three main technology providers (All Power Labs, Ankur Scientific and Husk Power Systems) has a successful project track record in SSA. All Power Labs manufactures sophisticated equipment in the USA but has not developed local supply chains and engineer training. Both Ankur and Husk Power make simpler and more robust systems and have reportedly installed hundreds of units in India, but have not been open to sharing information that confirms the successful and reliable operation of these projects.

The feedstocks worth pursuing for technical possibilities and replication potential are woody materials from trees and processing by-products, as well as the residues from seven widespread crops. Opportunities potentially exist for innovation in technology, business models and feedstock supply chains. Challenges lie in finding business models that are pro-poor but can at the same time be realistically managed within the capacity of small-scale industries, and also in building up suitable local technical and engineering capacity.

3.4 Combustion

3.4.1 TVC descriptions

The team initially identified around 40 examples in SSA of **biomass combustion systems powering steam turbines** for the production of heat or electricity. The vast majority, however, are bagasse-fuelled power plants in sugar mills, where this technology is well established. In South Africa alone there are at least 15 sugar mills with steam turbines, all of which were discounted from this research as the smallest (at Eston and Pongola) operate at 8.5 MW while the largest (at Felixton) produces over 30 MW (Enertime & ecosur afrique, 2012). Sugar mills in Kenya, Malawi, Sudan, Swaziland, Tanzania, Uganda and Zimbabwe were similarly discounted on the basis of scale, as were the installations at Siat Group's palm oil plant in Ghana (23 MW_{th} + 2.5 MW_{e}) and at the Mufindi Paper Mill in Tanzania (10 MW).

The remaining 12 TVCs are summarised in Figure 5.

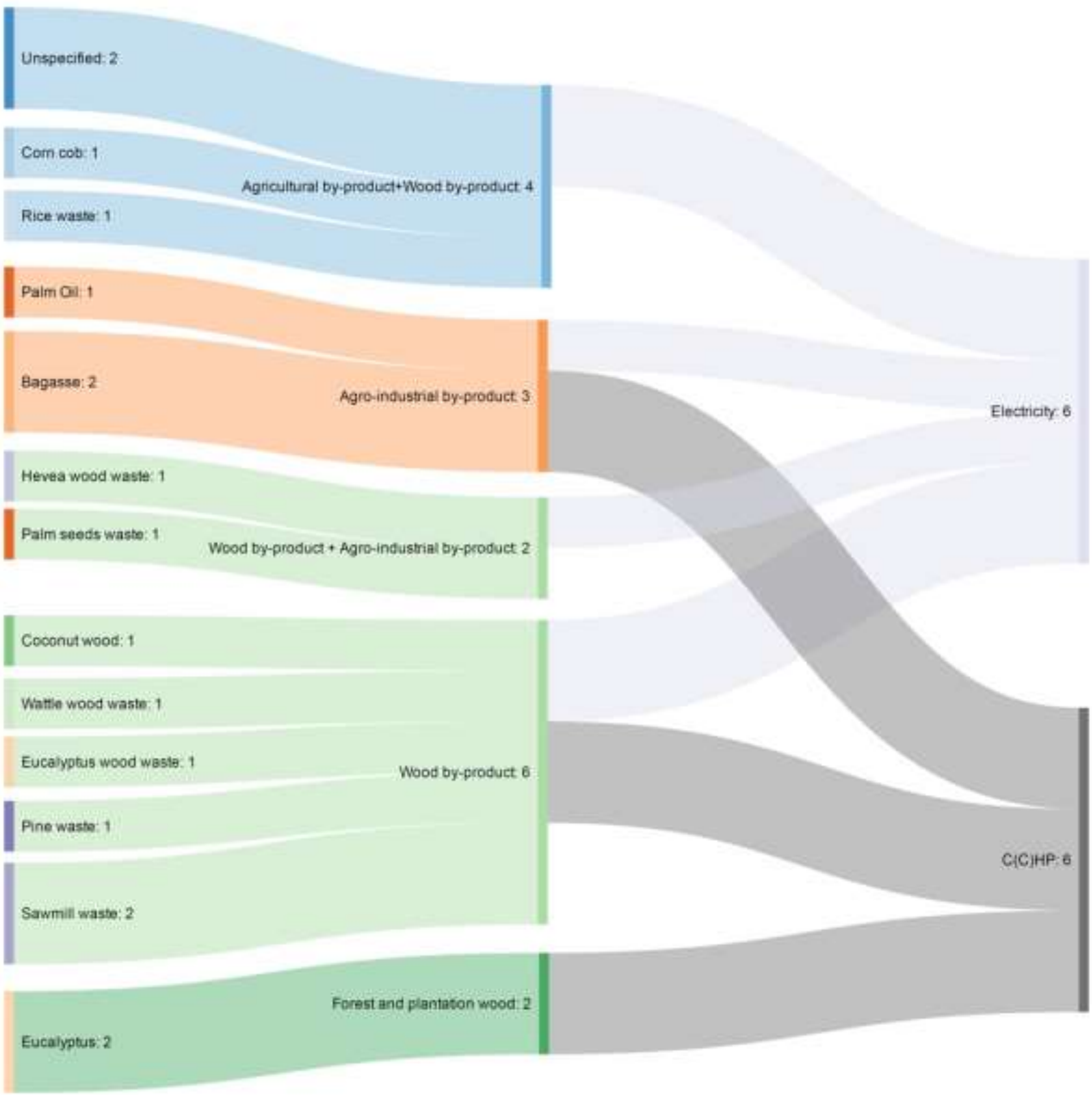

Figure 5. TVC profiles for combustion + steam turbine <5MW

Apart from 2 bagassed based CHP plants operational in Uganda, there is only one example of non-woody biomass being used exclusively for this technology, which was found at the Sania 640 kW_e plant in Abidjan, Côte d'Ivoire, fed with **palm oil waste** from the company's own large refinery (Enertime & ecosur afrique, 2012).

There are nine further examples of steam turbines being applied in the desired scale range, all of them fuelled with **woody biomass** exclusively or in combination with other feedstocks such as rice residue, corn cobs or palm seed waste.


TanWat power plant, Njombe. Tanzania

The largest installations are found at forestry operations, with a well-known example being the 2.5 MW_e plant at the Tanganyika Wattle Company (TanWat) at Njombe in southern Tanzania. **Wattle**, **eucalyptus and pine** are burned here to produce steam, both for the extraction of tannin from the wattle bark and for powering a tea factory, sawmill and grid feed-in. The cogeneration plant consists of two boilers and a single stage condensing steam turbine (Household Energy Network, 2004). The system has been running since 1995 and is reportedly still operational. A smaller (700 kW) plant using eucalyptus feedstock exists at Finlays Tea Estate in Kericho, Kenya. It is currently under repair due to over-heating of the super-heater (Douglas-Dufresne, 2017). Both the TanWat and Finlays plants employ US steam turbine technology.

A 1.1 MW steam turbine plant fuelled with **sawmill waste** was planned by the Société Forestière et Industrielle de la Doumé (a subsidiary of the ROUGIER Group) in Mbang, eastern Cameroon. Carbon finance was to be provided via UNEP's CASCADe[6] programme (UNEP, n.d.). An even larger (6 MW) steam turbine power plant is planned for the forest industry in Sokoban Wood Village of Ghana's Ashanti Region under an ambitious waste-to-energy project supported by GIZ, Kwame Nkrumah University of Science & Technology and the ECOWAS Centre for Renewable Energy and Energy Efficiency (Kwamoka Energy, 2017).

On Mafia Island off the coast of Tanzania, a 1 MW_e steam turbine run by Ngombeni Power is fuelled with **coconut wood**, from which the electricity is sold to the utility TANESCO at USD 0.301/kWh for a mini-grid serving the island's population (Greacen, 2014).

These installations are all relatively large in scale (at least 1 MW), have employed proven technologies from well-known suppliers and represent straightforward investment decisions by large commercial players based on known operating parameters. They are reportedly all operational and can be considered technologically successful.

The only smaller example found was an EU-funded 75 kW installation at Andaingo in Madagascar, managed through a partnership of Cirad, Ader & FOFIFA. 600 households

[6] Carbon Finance for Agriculture, Silviculture, Conservation and Action against Deforestation.

were reportedly being supplied with electricity at EUR 0.24/kW from a plant fed with community-owned **forest plantation waste** (Cirad, 2015).

3.4.2 Opportunities for BSEAA

Potential for innovation

Besides perhaps exploring opportunities for community-sourced feedstock, the innovation potential around steam turbine technology is quite limited. It had been thought during the previous phase of this assignment that uptake of this technology might have been impeded by the lack of lower capacity, off-the-shelf turbine systems for sub-5 MW applications: the absence of such devices might have been constraining replication in developing countries. However, further investigation has revealed that there are in fact a number of technology providers already offering compact steam turbines with outputs in the hundreds of kW, with a few examples listed in Table 6.

Table 6. Sample of suppliers of sub-5 MW steam turbines

Technology provider	Country	Output range	URL
G-Team	Czech Republic	80 kW - 5 MW	www.steamturbo.com/steam-turbines.html
Siemens	Germany	75-300 kW	www.energy.siemens.com/br/en/fossil-power-generation/steam-turbines/sst-040.htm
Elliott Group	USA	50 kW-3 MW	www.elliott-turbo.com/Turbines
Energent	USA	275 kW	www.energent.net/documents/microsteam_brochure.pdf
Valcon International	Czech Republic	150-300 kW	www.valcon-int.com/vidinis.php?id=1&id2=4
Skinner	USA	Above 140 kW	www.skinnerpowersystems.net/steam-turbines/

The technology innovation potential is therefore somewhat less than anticipated. The question is less about whether small-sized steam turbine units for biomass exist or can be developed, but why installations at this scale do not seem to be attracting interest in SSA for heat or power.

'Pro-poor' potential

CHP steam turbines for power, heat and cooling energy can be economically viable only as low as 250 kW_e (Douglas-Dufresne, 2017). This is a constraint to small-scale operation where there is greatest pro-poor potential. Furthermore, despite combustion powering steam turbines being a high TRL technology combination, it still requires a high degree of engineering expertise to operate and maintain these systems. There is a low probability that this would be found within communities or small enterprises. The main developmental opportunities lie in the engagement of communities in feedstock supply chains or through energy provision in off-grid or areas with an unreliable grid.

Prospects for DFID additionality

The high TRL level and existence of reliable technology at a range of scales limits the value that DFID could add to this particular technology through support to technology research.

3.4.3 Summary and implications

In summary, combustion powering steam turbines is a well-developed technology combination at TRL 9 with limited innovation potential. The majority of projects are located at sugar mills using bagasse (mostly >5 MW_e), while the remaining examples use wood processing by-products and plantation wood such as eucalyptus. Only one project below the 5 MW scale was identified in SSA and there is therefore no opportunity for informative case study analysis.

DFID's additionality would be to explore the technical and economic reasons for lack of uptake in agricultural, agro-industrial and forestry industries in SSA in the range 250 kW_e to 1 MW_e. The technology is known to be inefficient for power-only generation at these small scales, so there would need to be demands for cogeneration and the techno-economic viability of this option needs to be explored.

4. Conclusions

Research during this phase of the BSEAA study has revealed a surprising lack of bioenergy investment in SSA in the shortlisted technology areas at an operating scale of potential research interest to DFID. Anaerobic digestion for CHP is a sufficiently mature technology to have attracted commercial finance in South Africa and Kenya at large cattle farms and agri-businesses, but only at a few sites, and rarely in other countries. Gasification has no established track record in SSA besides a handful of donor-financed demonstration units that show mixed results, mostly in Tanzania and Uganda based on rice husk or maize waste. Biomass-powered steam turbines show a different uptake pattern and have been widely installed in the timber, paper and sugar industries, but rarely at sub-5 MW scale.

Anaerobic digestion is the most promising technology stream for TVC case study research. It offers innovation potential related to technology, feedstocks and business models and the commercial biogas sector is seeing a growing level of investment within the continent to which DFID could add momentum through targeted research support. Compelling benefits of the technology include:

- a high level of commercial advancement outside Africa from which to draw lessons and 'leapfrog' technologically;
- a high degree of feedstock flexibility across municipal, agricultural and livestock waste streams that enhances resilience and replicability;
- a relatively passive mode of enclosed fuel production that reduces (though does not obviate) the need for full-time feed management;
- the dispatchability of the energy from stored fuel (biogas); and
- co-benefits in the form of waste disposal and digestate production.

Gasification is a more ambiguous technology. The global track record at small scales has been inconsistent, with mass adoption in Indonesia, Thailand and India not sustained for reasons linked to feedstocks, technologies and economics. State of the art gasifiers are too complex to maintain in the absence of responsive manufacturer back-up and skilled technicians, while simpler technologies are proving polluting and unreliable. Failure rates over the medium-term are close to 100%, mainly due to the lack of maintenance know-how and spare parts. DFID could potentially contribute to advancement of gasifier technology or research into suitable industrial value chains.

There is limited innovation potential for **steam turbine** technology, but a lack of uptake in the 250 kW to 1 MW range merits further investigation into technical and economic feasibility of heat or power applications at this scale.

5. Next Steps

During the second half of April, the team will reach out to a representative selection of project developers and technology providers who work (or support work) in SSA. This process of outreach, which began during the stakeholder mapping and has continued during the TVC identification, will be a targeted process with direct requests to specific organisations for operational information, experience sharing and site visits.

The focus in case study identification will be on anaerobic digestion and gasification, for which the potential TVCs are summarised in Figure 6 and Figure 7.

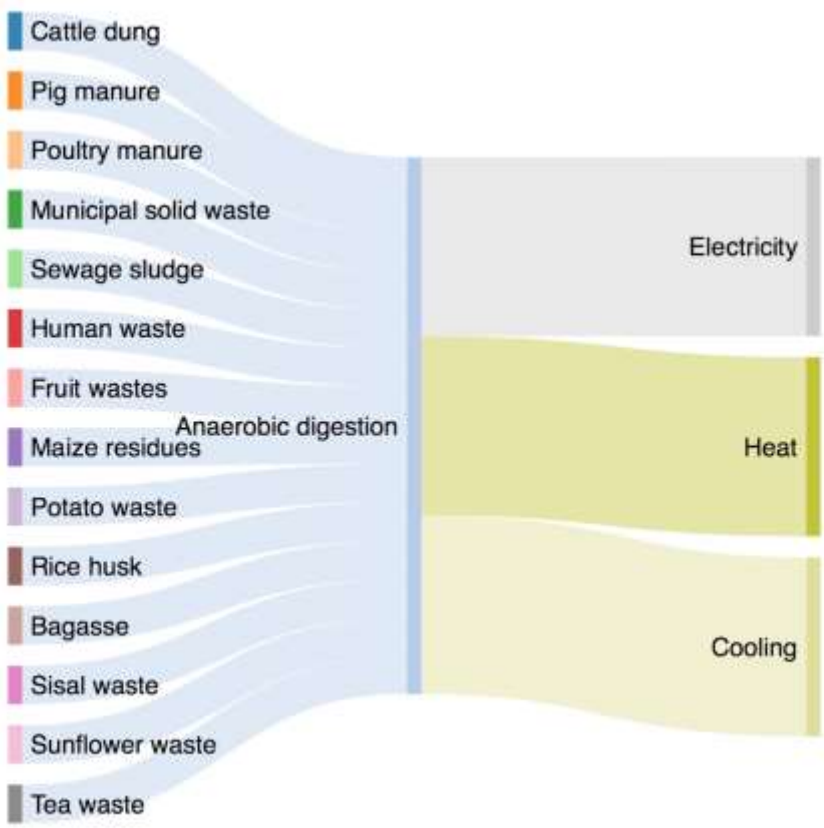

Figure 6. Proposed TVCs to be explored in anaerobic digestion case studies

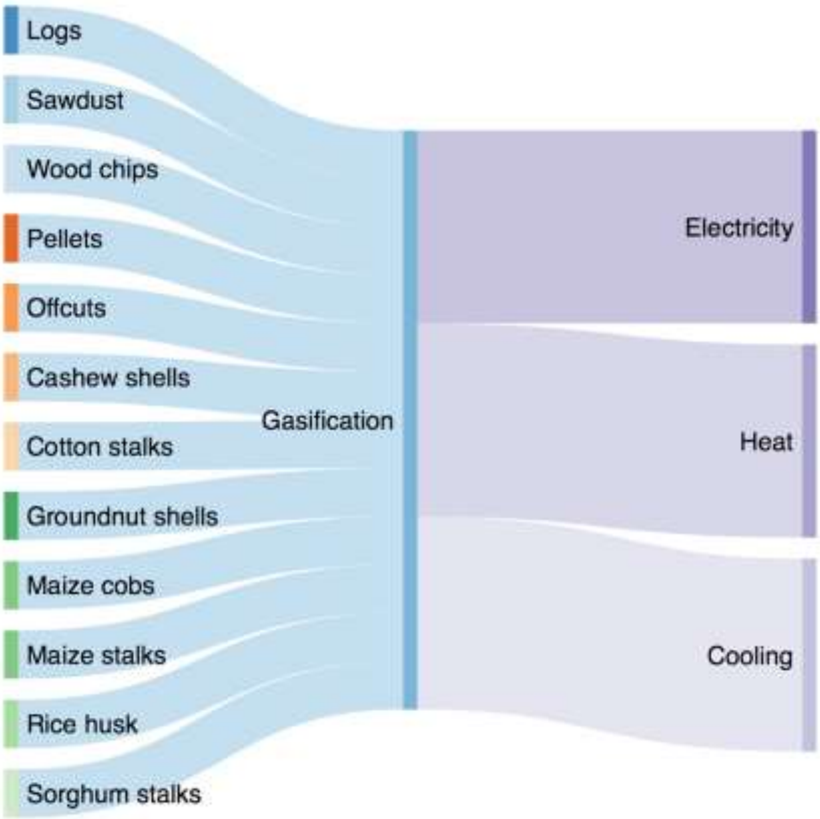

Figure 7. Proposed TVCs to be explored in gasification case studies

Case studies in Africa for these TVCs will be identified during April and site visits will be organised for May and June to explore:

1. **Innovation opportunities** around feedstock, technology and end use;
2. **Pro-poor impact potential** of different business models, especially considering feedstock supply or use of the energy produced; and
3. **Potential for DFID additionality**, where research could make a significant change to business-as-usual and enhance the prospects for replication.

Technology providers and project developers with African experience in Europe and Asia may also be consulted to explore barriers, opportunities and priority areas for research investment.

There are no steam turbine case studies to explore at the small operating scale. A short piece of desk-based research will instead be conducted to explore the technical and economic viability of biomass-fuelled steam turbines for heat or power at the sub-250 kW scale.

A report summarising the case study experiences and implications for Phase II research priorities is due at the end of July.

Annex A Google search strings for TVCs

Table 7 lists the search strings that were applied in the search for relevant examples of each bioenergy technology.

Table 7. Google search strings for identification of TVC examples

	Combustion + steam turbine	Gasification + internal combustion engine	Anaerobic digestion + internal combustion engine
English-speaking countries	• “biomass combustion” + "steam turbine" + country • “biomass combustion” + "steam turbine" + “cogeneration” + country	• “biomass gasification” + “engine” + country	• "anaerobic digestion" + “engine” + country • “biogas” + “engine” + country • “biogas” + “electricity”+ country
French-speaking countries	• “combustion turbine à vapeur” + country • “combustion” + country • “combustion biomasse” + country	• “gazéification moteur à combustion interne” + country • “gazéification moteur” + country • “gazéifieur” + country • “gazéifieur biomasse” + country	• “digestion anaérobie moteur à combustion interne” + country • “digestion anaérobie moteur” + country • “méthanisation moteur à combustion interne” + country • “méthanisation moteur” + country • “méthanisation” + country • “biodigesteur” + country • “biogas” + country • “méthanisation biomasse” + country • “biodigesteur biomasse” + country

Additional search terms such as ‘project’, ‘feasibility study’ or ‘case study’ were added to these search strings in cases where a very large number of results were returned..

Annex B People consulted during this phase

Name	Position	Organisation	Location	Nature of interaction		
				Email	Skype	In-person
Mary Abbo	Director	Centre for Research in Energy & Energy Conservation	Kampala	X		X
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Allison Archambault		Earthspark	US	X		
Godfrey Bakkabulindi	Secretariat Manager	GET FiT Uganda	Kampala	X		X
Bertrand Belben	Small scale Renewables and Off-grid	InfraCo Africa	London	X	X	
Nic Bennett	Director	SucroPower	Durban	X		
Martina Bergschneider	Managing Director	Southern BioPower	Lusaka	X		
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Sanne Castro	CEO	Simgas	Netherlands			X
Tim Chambers	Managing Director	Inspira Farms	Kenya	X		
Clementine Chambon	Chief Technology Officer	Oorja	London	X		X
Ashok Chaudhuri	Vice President, Business Development	Ankur Scientific Energy Technologies	Vadodara, India	X		
Steven Christopher	Commercial Director	DP Cleantech	Wolverhampton	X		
Benjamin Cok	Manager, Biogas to Milk Chilling Project	SNV	Dar es Salaam	X		
Tom Coogan	Regional Director	US-African Development Foundation	Washington, DC			
Elmar Dimpl	Energy and Transport Department	GIZ	Eschborn	X		
Hugo Douglas-Dufresne	Engineering Director	James Finlay Kenya	Kenya	X	X	
Alex Eaton	CEO/Co-founder	Sistema Biobolsa	Mexico / Nairobi	X		
Felix Ertl	Adviser	Pamoja Cleantech & Entrade	Germany	X	X	
Michael Franz	Team Leader	EU Energy Initiative – P'ship Dialogue Facility	Brussels	X		X
Mark Hankins	CEO	African Solar Designs	Kampala	X		
Johannes Heickmann	Investment Manager	KFW DEG	Cologne			X
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Geert Jan Heusinkveld	Business Development Consultant	Q Energy Biodigesters	Kampala	X		
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Peter Hutchinson	Executive Director	Green Africa Power	London	X		
Julien Jacquot	GEX Manager	Geres	Cambodia			X
Peter James	Manager of African Investments	AgDevCo	Dar es Salaam	X	X	
Craig Jamieson	Rice Straw Energy Project	International Rice Research Institute	Philippines	X		X
Wim Jonker-Klunne Darius Boshoff	Programme Director Biomass Energy Adviser	Energy and Environment Partnership for east & southern Africa	Pretoria	X	X	
Alec Joubert	Investment Director	Renewable Energy Performance Platform	Johannesburg	X	X	
John Kamau	Management Accountant	Cummins Cogeneration (Kenya)	Kenya	X	X	
Stephen Karekezi	Director	Energy, Env't. & Dev't. Network for Africa	Nairobi	X	X	
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Macben Makenzi	Project Advisor, East Africa	Powering Agriculture	Nairobi	X		
Rui Filipe Marques	Senior Engineer	Energias de Portugal, S.A.	Lisbon			X
Lucius Mayer-Tasch	Energy Access Ghana	GIZ/ECREEE	Praia, Cape Verde	X	X	
Marc Monsarrat	Founder	Power Progress	London			X
Tom Morton	Managing Director	Tropical Power	Nairobi	X		
David Muñoz	Technical Advisor	Ongawa	Madrid	X		
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Stephen Mutimba	Managing Director	Camco Clean Energy	Nairobi	X		
Timothy Mwogesa	Director	The Portico	Kampala			X
James Orima	Director	Earth Energy	Kampala			X
Jesse Owino	Area Manager	Kenya Forestry Research Institute	Lodwar, Kenya	X		X
Samuel Owusu-Takyi	Acting Director	Kumasi Institute of Tropical Agriculture	Kumasi, Ghana	X		
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Karen Price	Director	Nature Trust Malawi	Lilongwe	X		
Rudolf Rauch	Director Energy Programme Indonesia/ASEAN	GIZ	Indonesia	X		
Anjali Saini	Adviser	AECF Renewable Energy & Adaptation to Climate Technologies	Nairobi	X		
Hari Sharan	Chairman	Decentralised Energy Systems India	Switzerland	X	X	

Name	Position	Organisation	Location	Nature of interaction		
				Email	Skype	In-person
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Mike Smith	Director	Renen Energy Solutions	South Africa	X		
John Tate	Chairman & CEO	Ruaha Energy Company Limited	Dar es Salaam	X		
Jossy Thomas	Industrial Dev't. Officer, Renewable & Rural Energy	UNIDO	Vienna	X	X	
Vivian Vendeirinho	Managing Director and Founder	RVE.SOL	Leiria, Portugal			X
Shashank Verma	Head of Energy Advisory Team	Energy4Impact	Nairobi	X	X	
Chris Wilson	Managing Director	Biogas Power Holdings (East Africa)	Kilifi, Kenya	X		
Glen Wilson	Project Officer	European Biomass Association	Brussels	X		

Annex C TVC examples by technology type and country

Anaerobic Digestion + Internal Combustion Engine

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
Botswana	Botswana College of Agriculture	Gaborone	Pig manure	Electricity		?	Planned	http://bit.ly/2mJxrHt
	Dairy Power Box	Botswana	Cattle dung	CCHP	Selectra	100 kW	Operating	http://bit.ly/2nSJSAy
	Golden Links	Gaborone	MSW	Electricity		?	Pilot	http://bit.ly/2mXyGne
Burkina Faso	Fasobiogaz	Ouagadougou	Abattoir waste + brewery waste	Electricity	Gilbert Brenninkmeyer	275 kW	Operating	http://bit.ly/2naJ9O3
Cameroon	Bioenergy-Cameroon/ Green Girls Project	University of Buea and local schools	Latrine waste	Electriciy + cooking	Bioenergy-Cameroon	Small HH gen-sets	Planned	http://reut.rs/2gYTfgd http://bit.ly/2mXreIG http://bit.ly/2mgWPXR http://bit.ly/2mFEi3w
Cote d'Ivoire	Novis (Germany)		Cocoa shells	Electricity		Scalable to 2 MW	Closed	
Ethiopia	LIVES project (ILRI + Int'l. Water Management Institute)	Sebeta, Oromia region	Cattle dung	Electricity		4 m^3 biogas/day	Pilot	http://bit.ly/2n42yju http://bit.ly/2nowzvp
Gabon	Siat (Belgium))	Makoube	Palm processing waste	Electricity	?	1.2 MW	Operating	http://bit.ly/2mhrd5p
Ghana		Appolonia	Cattle dung, latrine waste	Electricity		12.5 kW	Closed	http://bit.ly/2iRINZH
		Ashaiman, Greater Accra	Market wastes, abattoir waste, community toilets	Electricity + others		100 kW	Pilot	http://bit.ly/2nABCsT
Kenya	Abdul Sidis farm	?	Vegetable residues	Electricity	?	20 kW_e	Operating	http://bit.ly/2naMq0a
	Biogas plant	Keekonyokie	Abattoir waste	Electricity + cooking		20 kW_e	Unclear	http://bit.ly/2naMq0a http://bit.ly/2naMq0a

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
	Biogas Power Holdings (East Africa); Kilifi Plantations	Kilifi	Cattle dung, sisal waste	Electricity	agriKomp GmbH	150 kW_e	Unclear	http://bit.ly/2mXAtso http://bit.ly/2naLRDe
	Finlays Tea	Kericho	Spent tea	CHP	AKUT Umwelt with Erwin Koeberle (Biogaskontor) and Tara Consult	160 kW_e + 170 kW_{th}	Operating	http://bit.ly/2nonkLO http://bit.ly/2noEoRz
	Olivado	Murang'a	Avocado waste	Electricity	?	300 kW	Under construction	http://bit.ly/2nSIBLe http://bit.ly/2mXsMST
	Teita Sisal Estate	Mwatate	Sisal waste	CHP			Unclear	http://bit.ly/2mFIFM2
	Tropical Power/ VegPro Group	Gorge Farm, Naivasha	Crop waste	CHP	Snow Leopard (technology), GE (gas boiler)	2.8 MW	Operating	http://bit.ly/2naM3IW http://bit.ly/2mhwRVb
	UNIDO, UNEP, Kenya Industrial Research & Dev't. Institute, Dagoretti abattoirs Association	Dagoretti	Abattoir waste	Electricity	?	10 kW_e	Closed	Email/interview (UNIDO)
Madagascar	CASIELEC	Anjiajia	Rice processing waste	Electricity	CASIELEC	80 kW	Unclear	http://bit.ly/2mXzlj6
Mauritius	Sotravic Ltd & Eneotech	Mare Chicose landfill	Landfill gas	Electricity		3 x 1.1 MW	Operating	http://bit.ly/2ljslj1 http://bit.ly/2mXv1FO http://bit.ly/2nSEbTn http://bit.ly/2mXt4sX http://bit.ly/2mFJKDv http://bit.ly/2nSEmhv http://bit.ly/2mXB65e http://bit.ly/2mhxgHb
Namibia	Gammams Water Care Works	Windhoek	Sewage sludge	CHP		2 x 250 kW_e + 494 kW_{th}	Planned	http://bit.ly/2nSn6ZZ http://bit.ly/2mJeJQh

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
	Namibia Dairies	Mariental	Cattle dung	Electricity?		?	Unclear	http://bit.ly/2nGghes http://bit.ly/2n4a5Pn
Nigeria		Lagos	Poultry litter	Electricity	Avenam biogas system	5 kW	Unclear	http://bit.ly/2nGtALV
	Ajima Farms, General Enterprise Nigeria,, Eco-Watts	Rije	Cattle dung	Electriciy + cooking		124 m^3	Under construction	http://bit.ly/2mFGCrB
	Avenam Links International	Abuja	Human and food waste	Electriciy + cooking	Own design	1.5 kW	Unclear	http://bit.ly/2nGtALV
Senegal	C3E + Thecogas Senegal	Sogas Abattoir, Dakar	Abattoir waste	Electricity		1,000 kWh	Unclear	http://bit.ly/2n3XUli http://bit.ly/2mFsTAS
	Novis (Germany)		Unspecified	Electricity	?	120 kW_e	Operating	
South Africa	Bakkavor t/a Spring Valley Foods	Bapsfontein	Fruit waste	Electricity		?	Pilot	http://bit.ly/2nAyj52
	Bio2Watt	Bronkhorstspruit, Tshwane Metropolitan area	Cattle dung	Electricity		4.6 MW	Operating	http://bit.ly/2noorLu http://bit.ly/28lWG7y
	Bio2Watt	Cape Dairy, Malmesbury	Cattle dung, other wastes	CCHP		4.8 MW	Planned	http://bit.ly/2n3WbN3
	Selectra		Cattle dung, waste water	CCHP	Selectra/Dairy Power Box	70 kW_e + 15 kW_{th}	Unclear	http://bit.ly/2mJwJd7
	Darling dairy farm	Darling	Cattle dung	Electricity	Cape Advanced Engineering	?	Operating	http://bit.ly/2noAIF8 http://bit.ly/2mhsSb9
	Dundee Biogas Power	Maybole Farm, Dundee	Cattle dung	Electricity		2.2 MW	Planned	http://bit.ly/2mFHLiz
	Farmsecure Carbon & Manjoh Ranch	Nigel	Cattle dung, potato waste	Electricity		?	Planned	http://bit.ly/2nADKAV
	Morgan Abattoir	Springs	Animal + vegetable waste	Electricity	Biogas SA	400 kW	Planned	http://bit.ly/2nAwyVx http://bit.ly/2mFH0X7
	Planning & Cost Engineering Services	Mandini, KwaZulu-Natal	Bagasse	Electricity		?	Pilot	http://bit.ly/2mXDqsZ
	Single Destination Engineering	Farm scale project	Pig + chicken manure	Electricity	Capstone (micro turbine)	2 x 65 kW	Planned	http://bit.ly/2nAyyNu

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
Tanzania	Katani Ltd. (sisal)	Hale estate, Tanga	Sisal waste	Electricity	BioEnergy Berlin with Chinese eqpt.	2 x 150 kW	Operating	http://bit.ly/2nSkQSf http://bit.ly/2mFxEuf
Uganda	Centre for Research in Energy and Energy Conservation	Jesa farm, Busunju village	Farm waste?	Electricity	CREEC?	?	Pilot	http://bit.ly/2mJzT0D
	FACT Foundation & GRS Commodities	Ssese Islands	Water hyacinth, cow dung	Electricity	Digester from Albers Alligator (Netherlands); biogas generator from Weifang Chaoran Gas Power Co. (China)	12 kW	Unclear	http://bit.ly/2naGCUb http://bit.ly/2mFHeNX http://bit.ly/2mFCqrK
	MPPL Renewable Energy	Gulu District	Maize silage, cow dung	CHP	GE Jenbaucher engine	1 MW_e + 600 kW_{th}	Planned	http://bit.ly/2mhy7r6
Zambia	Bremen Overseas Research & Development Association, Germany	Nr. Chuma	Sunflower waste, cattle dung, jatropha press cake	Electricity + cooking	Southern BioPower Ltd	50-1,000 m^3	Operating	http://bit.ly/2mFoC0w
	SNV	Zambia	Cattle dung	CCHP	Simgas and Mueller BV	?	Planned	http://bit.ly/2nGhD9k
Zimbabwe	?	Kushinga Phikelela nr. Marondera	Unspecified	Electricity	?	? (large demo)	Closed	http://bit.ly/2mhy66H

Gasification + Internal Combustion Engine

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
Benin	Novis (Germany)		Maize & cotton stalk	CHP	Ankur	11 kW	Closed	
	Novis (Germany)		Maize & cotton stalk	CHP	Ankur	35 kW	Closed	
	Songhai NGO Centre	Porto Novo	Tree pruning, rice husk, palm kernel cake	Electricity	All Power Labs	32 kW	Pilot	http://bit.ly/2nAAohz http://bit.ly/2mJCtn6
Burkina Faso	Novis (Germany)		Maize & cotton stalk	Electricity	Ankur	35 kW	Closed	
Chad	All Power Labs	Goundi	Maize cobs	CHP?	All Power Labs	18 kW_e	Unclear	http://bit.ly/2nowPdM
Ethiopia	Ethiopian Rural Energy Dev't. & Promotion Centre		Prosopis juliflora	Electricity	Not specified	not specified	Unclear	http://bit.ly/2mht1vj http://bit.ly/2mFEX5a
Ghana	?	Tamale	Unspecified	Ghana	All Power Labs	?	Operating	
	Kumasi Institute of Tropical Agriculture	Papasi, Offinso North District	Palm kernel shells	Electricity	All Power Labs	20 kW	Operating	http://bit.ly/2nAABBn http://bit.ly/2mFH7Sa
Kenya	Jomo Kenyatta Univ. of Agric. & Technology	Nairobi	Rice husk	Electricity	JKUAT	Not specified	Pilot	http://bit.ly/2mhtUE4 http://bit.ly/2mhxHBb
	Rea Vipingo	Vipingo, Kilifi	Sisal waste	Electricity	?	1.5 MW	Unclear	http://bit.ly/2nGkuyS
	Tower Power Ltd.	Marigat, Baringo County	Prosopis juliflora	Electricity	Cummins	2.4 MW (12 MW planned)	Under construction	http://bit.ly/2nGkuyS
	Turkana Basin Institute	Turkana	?	Electricity	All Power Labs	10 kW	Closed	http://bit.ly/2n44yYS
	Unspecified wood processor	Unknown	Wood waste	CHP?	Fengyu Corp. (China)	1 MW	Unclear	http://bit.ly/2n48Jnx http://bit.ly/2nGjrz1 http://bit.ly/2mhvA0j
Liberia	Booker Washington Institute	Kakata	Rubber trees	CHP?	All Power Labs	18 kW_e	Unclear	http://bit.ly/2nSuaFQ
Malawi	Chelinda Lodge & Total Land Care	Nyika National Park	Waste pine wood	Electricity	All Power Labs	18 kW_e	Unclear	http://bit.ly/2nSwtsf
Mozambique	Sociedade Algodoeira do Niassa	Titimane	Cotton residues	Electricity	Not specified	?	Unclear	http://bit.ly/2mFJ1Tb http://bit.ly/2mJsZZb http://bit.ly/2nSFfqp

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
Namibia	University of Fort Hare (SA)	Melani village	Sawdust, groundnut shells, sunflower husk	Electricity	Carbo Consult	250 kW - 3 MW	Unclear	http://bit.ly/2nG7s4p http://bit.ly/2mFMmBj http://bit.ly/2mXuGTN http://bit.ly/2noASXt http://bit.ly/2nGo109
	Desert Research Foundation, National Farmers' Union, Agricultural Union	Farm Piere, Outjo District	Invader bush	Electricity		250 kW	Closed	http://bit.ly/2nSILkA http://bit.ly/2noHzIX http://bit.ly/2mXDGIr http://bit.ly/2mFJsgh http://tmsnrt.rs/2naPGsg
Nigeria	UNIDO	Ohaukwu, Ebonyi State	Wood chips	Electricity	IISc Bangalore	32 kW, 5 MW	Operating	http://bit.ly/2noCcd1 http://bit.ly/2naFyja
Senegal	Novis (Germany)	Kalom	Sorghum waste, peanut shells	CHP	Ankur	32 kW_e	Closed	http://bit.ly/2mXGpSd
	Novis (Germany)		Rice husk	CHP	Ankur	70 kW	Closed	
	Novis (Germany)		Unspecified	Electricity	?	100 kW?	Operating	
South Africa	Eskom, University of Fort Hare	Melani, Eastern Cape	Sawmill pine waste	Electricity	System Johansson	150 kW	Pilot	http://bit.ly/2naROAe
	Innov8	18 globally	Wood, wood residues	Electricity	Black Swan Group	10-250 kW	Unclear	http://bit.ly/2nACDkU
	Recor International	Nampo village	Sawmill waste	Electricity		25 kW	Unclear	http://bit.ly/2nAArdh
Tanzania	?		Cashew shells	Electricity	TERI	75 kW_e	Planned	Info from Jossy Thomas, UNIDO
	Ageco Energy & Construction	Magungumka	Rice husk	?	?	32 kW_e	Planned	http://bit.ly/2jgYqYu
	Continental Energy Corporation	Kilosa District	Unspecified	Electricity	Husk Power Systems	?	Operating	http://bit.ly/2nozcx7
	Husk Power Systems	Nyakagomba, Geita district	Rice husk	Electricity	Husk Power Systems	10 x 32 kW	Unclear	http://bit.ly/2mJD7kL
	Kilombero Plantations	Kilombero	Rice husk	Electricity	Husk Power Systems	0.5 MW	Operating	http://bit.ly/2nGsgZI
	ONGAWA Engineering for Human Development	Mbingu, Kilombero District	Rice husk	Electricity		32 kW	Unclear	http://bit.ly/2n4bRzL

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
	Ruaha River Power Co.	Dar es Salaam	Agri residue	Electricity	Husk Power Systems	32 kW	Closed	http://prn.to/2noLh5x
	Space Engineering Co.	Kimanzichana & Mwalusaga, Mkuranga District	Ag waste, forest residue	Electricity	Ankur	120 kW	Planned	http://bit.ly/2mJwrD4
Uganda	Entrade	German forest plantation	Wood waste pellets	CHP	Entrade	?	Planned	Info from Felix Ertl
	James Finlay Tea	Muzizi, Kibale District	Eucalyptus	Electricity	Ankur; Cummins	180 kW_e	Closed	http://bit.ly/2nStsZ0 http://bit.ly/2n4pvD9 http://bit.ly/2n464dw
	Kaesenge Electricity Power	Mukono	Eucalyptus	Electricity	Ankur	10 kW	Closed	http://bit.ly/2n4pvD9 http://bit.ly/2mFJ6WW
	Nyabyeya Forestry College	Masindi	Sawmill waste	Electricity	?	50 kW	Closed	http://bit.ly/259KENj
	PAMOJA Cleantech	Kamwenge District	Maize cobs, ag residue	CHP	Open tender	50 kW_e	Planned	http://bit.ly/2nSpqA6 http://bit.ly/2mFr47e
	PAMOJA Cleantech	Tiribogo, Mpigi District	Maize cobs, ag residue	Electricity	Husk Power Systems	32 kW_e	Operating	http://bit.ly/2nSuZyy
	PAMOJA Cleantech	Sekanyoni, Mityana District	Maize cobs, ag residue	Electricity	Husk Power Systems	11 kW_e	Operating	http://bit.ly/2nSuZyy
	PAMOJA Cleantech	Opit Youth Training Centre, Gulu	Maize cobs, ag residue	Electricity	All Power Labs	?	Closed	
Zambia	UNIDO	Kaputa	Wood, wood waste, ag residue	Electricity		2 x 500 kW	Unclear	http://bit.ly/2nGfLx0 http://bit.ly/2mJj2uV http://bit.ly/2nGfSZs http://bit.ly/2naNnWh http://bit.ly/2nSB6mg

Combustion + Steam Turbine

Country	Project developer	Location	Feedstock	End-use	Technology provider	Capacity	Status	Links
Burkina Faso	SOPAL distillery	Banfora	Bagasse	Electricity	?	3 x 1700 kW	Operating	http://bit.ly/2naK4y2
Cameroon	Société Forestière et Industrielle de la Doumé,	Mbang	Sawmill waste	Electricity		1.1 MW	Planned	http://bit.ly/2nAJj2i
Cote d'Ivoire	SANIA/SIFCA	Abidjan	Hevea wood waste + palm seeds waste	Electricity	SIFCA	640 kW	Unclear	http://bit.ly/2n48rgw http://bit.ly/2naVZw2
Ghana	Kumasi Waste to Power Project	Sokoban, Ashanti	Ag/forestry residue	Electricity		6 MW	Planned	http://bit.ly/2mJlgtV
Kenya	James Finlay Kenya	Kericho	Eucalyptus?	CHP	Steam turbine from US, switchgear & alternator from India	700 kW	Closed (refurb.)	
Madagascar	Bioenergelec	5 communes	Wood, rice & maize waste	Electricity	?	Diverse	Closed	http://bit.ly/2mJDdZi
	PSI Therma Metalurgica LTDA	Andaingo	Eucalyptus robusta	CHP	Gesforcom	75 kW	Unclear	http://bit.ly/2nADZfu
Nigeria	Quintas Renewable Energy Solutions	Ofosu	Sawdust/Ag/forestry residue	CHP?	Steam turbine made in Nigeria	500 kW	Planned	http://bit.ly/2jgYqYu
Swaziland	?	?	Bagasse, wood pulp	CHP	?	?	Unclear	http://bit.ly/2noGMrL
Tanzania	Kagera Sugar Limited	Kagera	Bagasse	CHP		2 x 2.5 MW	Operating	http://bit.ly/2mJxKli
	Ngombeni Power	Mafia Island	Coconut wood	Electricity		1 MW_e	Operating	http://bit.ly/2mFBCmA
	Tanganyika Wattle Company	Njombe	Wattle wood, eucalyptus wood, pine waste	CHP	Steam turbine from US, Generator from Germany, manufacturer from Malaysia	2.5 MW_e	Operating	http://bit.ly/2nGgLS3 http://bit.ly/2nABM3N http://bit.ly/2mJxKli
Uganda	Kakira Sugar Factory	Kakira	Bagasse	CHP		4 MW	Operating	http://bit.ly/2nGtHqN
	Kinyara Sugar Factory	Kinyara	Bagasse	CHP		2 MW	Operating	http://bit.ly/2nGtHqN

Annex D Feedstock classification for TVCs

Biomass feedstocks were assigned to one of eight categories in order to characterise Technology Value Chains. The team adapted the classification system of FAO (2004), as summarised in Table 8.

Table 8. System used for classifying biomass feedstocks for TVC characterisation

Feedstock Category	Sub-Category	Description	Examples
Woodfuels	Forest and plantation wood	Wood from forests, shrubs and other trees either used directly as fuel or with minimal processing	Eucalyptus, Prosopis spp., rubber tree
	Wood by-products	Wood derived from wood processing for other purposes	Sawmill waste, pine waste, wattle wood
Agro-fuels	Energy crops	Plants or crops grown explicitly or available naturally for the production of biofuels	Bamboo, dhaincha (*Sesbania spp.*), water hyacinth
	Agricultural by-products	Mainly by-products from crop harvesting and other agricultural activities left in the field	Rice husk, maize cobs, but shells
	Agro-industrial by-products	Biomass materials produced chiefly from inedible feedstocks used in food and fibre processing industries	Bagasse, palm oil mill effluent, sisal waste
Others (including mixtures)	Animal by-products	Waste and by-products from poultry and livestock	Manure, litter, slaughterhouse waste
	Horticultural by-products	Waste from non-staple plants such as fruits, flowers or ornamentals	Pineapple residues, flower waste
	Municipal by-products	Solid and liquid wastes produced directly by humans	Municipal solid waste, sewage sludge, human waste

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