Bioenergy for Sustainable Energy Access in Africa

PO 7420

Project Completion and Handover Report

Submitted to DFID
by LTS International Limited, the University of Edinburgh and E4tech

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Acronyms

BSEAA	Bioenergy for Sustainable Energy Access in Africa
CAM	crassulacean acid metabolism
DFID	Department for International Development
SSA	Sub-Saharan Africa
TRL	Technology Readiness Level
TVC	Technology Value Chain

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Executive Summary

Introduction

Between September 2016 and August 2017, a consortium of LTS International, E4tech and The University of Edinburgh implemented Phase I of the DFID-funded Bioenergy for Sustainable Energy Access in Africa (BSEAA) research assignment. This 12 month study set out to investigate the challenges and opportunities affecting the adoption and roll out of bioenergy technology across Sub-Saharan Africa (SSA).

Phase I was to define the scope of any future research in this area, through which DFID may support targeted research into the identified barriers and opportunities, and the development of innovative solutions. We also understood that DFID is intending to implement further research in this area under the larger Transforming Energy Access (TEA) Programme, which will test innovative technology applications and business models to accelerate the provision of affordable, clean energy-based services.

This report, the final output of BSEAA Phase I, summarises the various stages of the study, the reports that were produced and the implications for any future research in this area.

The five reports produced during Phase I are as follows:

1. Inception Report
2. Literature Review and Stakeholder mapping Report
3. Technology Value Chain Prioritization Report
4. Technology Country Case Study Report
5. Project Handover and Completion Report (this document)

Inception phase

During a six-week period of study design in late 2016, it was agreed that bioenergy technology would be analysed in the context of 'Technology Value Chains' that originate with biomass feedstocks that are converted to solid, liquid or gaseous biofuels, and in turn to bioenergy for heat, power, cooling or transport applications. DFID confirmed an interest in commercial bioenergy at community, institutional and industrial scales with an output range of 10 kW_e to 5 MW_e. It was also agreed to focus on technologies at Technology Readiness Level (TRL) 5 to 9.

Literature review and stakeholder mapping

Approach

A list of 27 potential bioenergy conversion technologies was reduced to 15 options for further analysis based on TRL status, operating scale, existence of functioning examples, prospects in SSA, appropriateness (in terms of technological sophistication, infrastructure requirements and social workability) and innovation potential. The shortlisted technologies were then investigated through review of academic and non-academic literature, and mapping of stakeholders in SSA's bioenergy sector, to provide evidence for narrower technology prioritisation. SSA countries were also screened to identify those with closest synergy with DFID interests, most conducive commercial environments, highest indications of bioenergy demand, greatest interest levels and optimal impact potential.

Findings

Based on the volume and nature of academic research, as well as a composite score from the non-academic literature that considered deployment level, appropriateness, replication potential, competitiveness and innovation opportunities, the following technologies were selected for more in-depth investigation:

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

Ten countries were at the same time prioritised for BSEAA research (Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Rwanda, South Africa, Tanzania, Uganda and Zambia). Stakeholder mapping during this phase also generated a network of project developers, technology providers, investors and development agencies for further information gathering.

Technology Value Chain prioritisation

Approach

Having identified ten promising countries and three technologies for more in-depth investigation, the study then set out to prioritise TVCs that combined these technologies with particular feedstocks and end uses. It was agreed that a shortlisted TVC for each technology should have been attempted in at least one verifiable example in SSA within the last decade at 10 kW to 5 MW scale. Systematic web searches and stakeholder investigation identified qualifying examples, with operational details verified through personal contact.

Findings

The research generated a database of 153 project examples in SSA using a wide variety of feedstocks, though fewer than 100 installations had been constructed and a majority were no longer believed to be functioning, especially among the gasification projects. TVCs were prioritised based on current or recent reported operation. Even those project developers and financiers specifically interested in developing bioenergy opportunities in Africa were found to have taken only a few initiatives beyond the stage of feasibility assessment.

Anaerobic digestion was deemed the most promising technology for case study research. As well as offering 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, offers significant feedstock flexibility across multiple waste streams, represents a relatively passive mode of fuel production, offers despatchable energy and provides co-benefits from waste disposal and digestate production.

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

No **steam turbine** installations were found at small scale in SSA, so no opportunity arose for case study analysis. It was agreed instead that desk research would be conducted into the technical and economic feasibility of sub-1 MW heat or power applications and potential innovation opportunities that might exist.

During the next phase, a sample of anaerobic digestion and gasification projects were to be selected as working examples of the prioritised TVCs from which to draw experiences and lessons. These would be described in Case Study Reports identifying the main barriers and opportunities for replication and innovation, giving an indication of research areas that DFID might usefully support in the future.

Country Case Study analysis

Approach

From the database of bioenergy projects in SSA, 45 examples were identified of anaerobic digestion systems linked to gas or dual-fuel engines for heat or power in the desired scale range. Output was split roughly equally between large (>1 MW_e), medium (0.1-1 MW_e) and small (<100 kW_e) installations. Just 12 were thought to be functioning and a similar number with unclear status were also potentially operational. 47 examples were meanwhile identified of gasifiers powering engines to deliver heat or power, the majority of them below 100 kW_e. Of the 13 gasifier projects that had reached implementation stage, no more than seven were believed to be operational.

18 of these biogas and gasification plants were then visited in seven SSA countries. The aim at each site was to identify barriers to replication that DFID-supported research could potentially address. Visits to biomass-based steam turbine plants were not feasible as no small-size installations could be identified. Parallel desk research

was instead carried out into sub-1 MW steam turbines to identify research and innovation opportunities.

Identified Barriers

It was found that six types of barriers are experienced by developers of **anaerobic digestion** projects:

Barrier 1: Unreliable feedstock supply

All of the successful biogas projects have sufficient feedstock on-site as a by-product of the developer's own business or an adjacent business with an equity stake. There was no successful example where the primary feedstock was being brought in from elsewhere. Novel feedstocks (e.g. lignocellulosic materials or dryland plants) may represent a breakthrough in expanding the range of feedstock options for SSA.

Barrier 2: Costly and insufficiently adapted technology

The high cost of European and North American biogas systems is a barrier to investment in SSA. Technology transferred without modification may also prove inappropriate for local operating conditions. For replication beyond well-resourced agribusinesses, cheaper designs are needed – potentially from Newly Industrialised Countries - that are adapted to the local context.

Barrier 3: Limited operator technical capacity

Insufficient operator skills have in some cases led to technical problems such as incorrect substrate temperature, pH, solids content or microbiological conditions. Systems have under-performed or broken down as a result. There is a need to elevate skill levels through training and operational exposure.

Barrier 4: Lack of viable business models

A number of factors are resulting in unviable business models. Besides insecurity of feedstock supply, they include reliance on a sole income stream, which is rarely a viable biogas strategy in SSA; and insufficient financial engagement of project owners resulting in commercially unrealistic models. Projects fully funded by donor grants have encountered viability problems. There is a need to prioritise sites that allow valorisation of multiple outputs. Given also the lack of commercial financing for biogas in SSA, donor resources need to be applied more strategically.

Barrier 5: Unfavourable policy and regulation

Most early developers of biogas projects target captive heat and power demand within agri-businesses. Replication beyond captive sites requires a supportive framework of government incentives, such as attractive feed-in tariffs and fair access to the grid.

In many SSA countries, environmental regulations are not enforced and polluters may face no penalties for waste dumping. This makes investment in biogas less economically attractive as a waste clean-up technology.

Barrier 6: Limited access to manufacturer support and spare parts

Only one European biogas technology provider has permanent representation in SSA, so plant managers must usually be self-contained with their own in-house personnel. Lack of local support and poor access to spare parts dis-incentivises further uptake of the technology.

The developers of the six **gasification** projects that were visited had meanwhile encountered more significant barriers that make replication very challenging:

Barrier 1: Feedstock quality and availability constraints

Sensitivity to feedstock specifications means that gasification is an inflexible technology, which limits the potential feedstock range and supply-side adaptability.

Barrier 2: Technology limitations

Operating parameters must adhere to precise manufacturer specifications or high outputs of char, tar and particulate matter may cause cleaning problems, result in engine failure and the generation of excessive toxic by-products. Small-scale gasification also lacks the same degree of power despatchability as other energy technologies, requiring a gas storage system or battery bank.

Barrier 3: Lack of viable business models

Anchor customers are often lacking in the profiled projects, none valorise heat or char, and all were financed to some extent with donor funds. These factors have resulted in commercially unrealistic models and have often led to over-sized systems.

Barrier 4: Limited operator technical capacity

It is challenging to secure the skills required to operate gasification systems in rural locations. There are few qualified individuals who can operate and maintain them successfully, compounding the problem of reliability and reputation.

Barrier 5: Poor access to manufacturer support and spare parts

All gasification equipment is imported to Africa and only one supplier is represented on the continent, resulting in limited access to technical support or spares. The absence of technical back-up further degrades the reputation of gasification.

Finally, the study confirmed the poor efficiency of **steam turbines** compared to alternative technologies at sub-1 MW output levels, for inherent technical reasons. There may still be opportunities to retrofit steam turbines for CHP in agri-businesses with an existing heat generation system and significant electricity demand in countries with high electricity costs (e.g. Kenya, Rwanda and Ghana).

Potential research opportunities

In defining the limits of further research support from DFID, the team proposed a focus on **anaerobic digestion**. Case Study research into the small number of functioning **gasification** plants in SSA confirmed that the barriers to replication are so significant and wide-ranging, especially in small-scale community settings, that there is no realistic opportunity for research to boost replication potential and it is not proposed that gasification-related research is supported. Desk research into the technical and economic feasibility of sub-1 MW heat or power applications from **steam turbines** reveals potential for retrofitting for CHP at plants with a functioning heat generation system and significant electricity demand. Further feasibility research on this theme is a supplementary option for future research.

Project completion and handover

Future DFID support for research is expected to respond to the identified challenges facing the deployment of bioenergy in SSA by exploring appropriate solutions. The emphasis will be on those barriers for which research can offer particular value over other types of intervention. Research that addresses technological barriers will be prioritised.

Assuming a technology focus on anaerobic digestion, examples of potentially relevant research themes to address the identified barriers are offered in section 6.2 (and in full in the Technology Country Case Study Report). An open call would elicit a wider variety of ideas that DFID can screen for relevance and impact potential. DFID may choose to focus on a sub-set of the barriers in framing its call, to maximise the impact of available resources.

The study team will ensure that the outputs of the Phase I research are handed over to the TEA Programme management. Core team members from LTS and E4tech will meet with the TEA programme Managing Agent to ensure that the richness and intent of the supporting analysis is also conveyed verbally.

Cooperation with other donor-funded programmes such as the Africa-EU Renewable Energy Cooperation Programme would be valuable to maximise effectiveness and reach.

1. Introduction

Between September 2016 and August 2017, a consortium of LTS International, E4tech and The University of Edinburgh implemented Phase I of the DFID-funded Bioenergy for Sustainable Energy Access in Africa (BSEAA) research assignment. This 12 month study set out to investigate the challenges and opportunities affecting the adoption and roll out of bioenergy across Sub-Saharan Africa (SSA), and support the development of innovative bioenergy solutions for developing countries.

Phase I was to define the scope of any future DFID investment in this area, through which DFID may support targeted research into the identified barriers and opportunities facing bioenergy technologies in SSA.

This report, the final output of Phase I, summarises the various stages of the study, the content of the reports that were produced and the implications for any future research in this area. The research team is also conducting a handover to the TEA programme management consortium to ensure that the Phase I process and its outcomes are appropriately incorporated.

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2. Inception Phase

2.1 Scope of Work

BSEAA Phase I officially got underway on 20th September 2016. During a six-week Inception Phase the study methodology was outlined in more detail, a logical framework was developed and a reporting schedule and milestones for each output were agreed upon.

From the outset, bioenergy was taken to refer to the energy generated from the conversion of solid, liquid or gaseous biofuels, which have in turn been derived from biomass feedstocks. Biomass, biofuels and bioenergy represent sources, trade forms and delivered heat, power and transport, respectively, as illustrated in Figure 1.

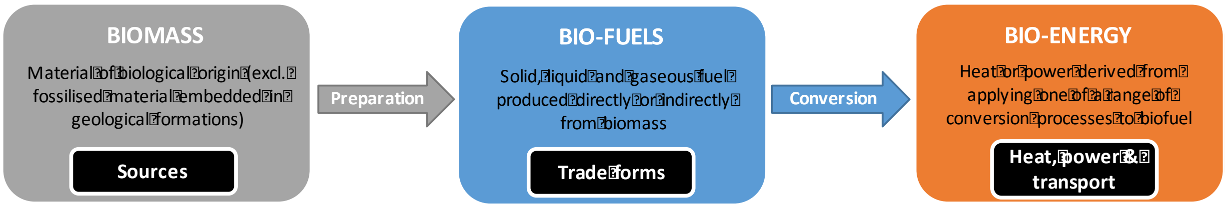

Figure 1. Bioenergy definitions

During an initial call and kick-off meeting, DFID confirmed a focus on commercial bioenergy applications at community, institutional and industrial scales. Technologies for household installation were to be excluded, unless viable models of centralised management should emerge. An output range of 10 kW_e to 5 MW_e was later agreed.

The team's proposed basis for analysis was the Technology Value Chain (TVC), comprising a feedstock, a conversion or processing technology and an energy application. In light of DFID's interest in technology-based solutions, technological considerations were to underpin the shortlisting of opportunities during the subsequent literature review and stakeholder mapping tasks.

Having agreed with the DFID lead adviser that bringing entirely new technologies to market would be beyond DFID's current ambitions for any future research in this area, it was agreed to focus on those that have already demonstrated potential in Africa or have been successfully introduced elsewhere with good indications of transferability. This was defined more precisely during the Inception Phase as Technology Readiness Level (TRL)[1] 5 up to 9, meaning large scale piloting to full commercial availability.

[1] Technology Readiness Level reflects the development status of a technology. It is a relative measure of maturity on a scale of 1 to 9.

2.2 Logical framework and workplan

The Phase I research was designed to build up an evidence base that would guide any future research into the challenges and opportunities for expansion of prioritised bioenergy technologies in selected SSA countries. A logical framework guided the drafting of a study work plan, which is summarised in Table 1.

Table 1. Abridged version of BSEAA Phase I work plan

	2016				2017								
	Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Task 1: Inception/Design	■	■											
Output 1: Inception Report		■											
Task 2: Bio-energy Sector Analysis			■	■	■								
Output 2: Lit. Review & Stakeholder Mapping Report						■							
Task 3: Technology Value Chain Prioritisation					■	■	■	■					
Output 3: Tech. Value Chain Prioritisation Report								■					
Task 4: Case Study Country Scoping							■	■					
Task 5: Country Case Studies									■	■	■		
Output 5: Technology Country Case Study Report, incorporating Output 4: Country Scoping Reports											■		
Task 6: Project completion and handover												■	■
Output 6: Project Completion and Handover Report												■	

As indicated, six written Outputs were envisaged. Approval was later given by the DFID lead adviser to merge Outputs 4 and 5. Phase I has therefore generated five reports (including this one) that DFID will make publicly available (see Table 2).

Table 2. BSEAA Phase I Reports

Study Output	**Contents**	**Date**
1. Inception Report	Confirmation of assumptions; amendments to approach; logframe, deliverables and workplan; expanded methodology; quality plan; communications protocol.	9 Nov 2016
2. Literature Review and Stakeholder Mapping Report	Analysis of academic and commercial bioenergy publications to identify technologies with uptake or expansion potential in SSA. Profiling of academic, commercial and public sector investment landscape in bioenergy technology in SSA. Country screening to define potential DFID investment locations.	17 Feb 2017
3. Technology Value Chain Prioritisation Report	Analysis of TVCs across shortlisted countries, including feedstocks, technologies, end uses and enabling conditions. Prioritisation of 3-5 TVCs for further research in Phase II.	20 Apr 2017
4. Technology Country Case Study Report (incorporating Country Scoping Reports)	Analysis of Case Study examples in SSA, documenting challenges and opportunities for the deployment of shortlisted bioenergy solutions in real-world settings (incorporating Country Scoping Reports documenting meetings held during country visits).	8 Aug 2017
5. Project Completion and Handover Report	Summary of process, learnings and implications, as consolidated handover document for Phase II.	31 Aug 2017

2.3 Study phases and outputs

2.3.1 Literature review and stakeholder mapping

The study itself began in November 2016 with a literature review and stakeholder mapping phase. This was designed to shortlist bioenergy technologies at TRL 5-9 deemed to have the greatest potential for large-scale uptake in SSA, based on levels of research interest and direct investment by public and private sector actors. Initial stakeholder mapping also provided an indication of countries with higher levels of bioenergy activity; and generated a provisional network of project developers, technology providers, investors and development agencies for further information gathering during the follow-on TVC prioritisation process.

The full list of 45 countries in Sub-Saharan Africa was also to be reduced to a more realistic and manageable set of 10-15, based on a set of objective criteria.

These processes were together intended to deliver a shortlist of three to five technology options in 10 to 15 countries for TVC prioritisation, which were summarised in a Literature Review and Stakeholder Mapping report (see section 3).

2.3.2 TVC prioritisation

During the TVC Prioritisation Phase, a database was developed of projects in SSA that featured the shortlisted technologies. TVCs were prioritised from this database that combined the technologies with particular feedstocks and end uses, and offered potential for replication. This process was summarised in a TVC Prioritisation Report (see section 4).

2.3.3 Country Case Study analysis

For each shortlisted technology, a set of representative case studies was then identified and visited across a representative sample of the prioritised countries. These provided working examples from which to research the practical barriers and challenges to deployment of each technology in high opportunity countries. The case studies and identified barriers are summarised in a Technology Country Case Study Report (see section 5).

2.3.4 Project completion and handover

This summary report documents the entire research process and brings together the findings and recommendations of each previous phase. The individual reports should also be read to gain a richer understanding (see Table 2).

3. Literature Review and Stakeholder Mapping

3.1 Approach

The substantive programme of work got underway between November 2016 and February 2017 with the Literature Review and Stakeholder Mapping phase.

27 bioenergy technologies were initially identified at TRL 5 and above. Given that DFID's scale of interest lies above households but below large industry, an output ceiling of 5 MW_e or 10 Ml/yr was applied to pre-screen technologies, and several were eliminated on this basis. Others were eliminated due to a global lack of operational examples, negligible prospects for piloting in SSA or an absence of necessary infrastructure. This left 15 potential conversion technologies for further investigation (Table 3).

Table 3. Shortlisted technology options for BSEAA research

Primary conversion technology	Secondary conversion technology	End use					
		Heat	Power	C(C)HP*	Transport	Cooking	Other
Combustion	None	x					
	Steam turbine		x	x			
	Steam engine		x	x			
	Stirling engine		x	x			
	Organic Rankine cycle		x	x			
Gasification	Internal combustion		x	x			
Fast pyrolysis	Combustion	x	x	x			
Slow pyrolysis	Internal combustion		x	x		x	x
Oil pressing	Internal combustion		x	x	x		
	Transesterification				x		
Anaerobic digestion	None					x	
	Internal combustion		x	x			
Fermentation	Ethanol fermentation				x	x	x**
	Butanol fermentation				x		
Microalgae							Oils

* C(C)HP = Combined (cooling) heating and power
** Ethanol can be used indirectly for power and C(C)HP, via an internal combustion engine.

The shortlisted options were then investigated further through an in-depth literature review. Published journal papers were analysed for volume, content, theme and geographic focus, while non-academic publications from commercial and publicly funded bioenergy initiatives were screened for relevance, content and implications for technology prioritisation. The landscape of actors in SSA's bioenergy technology sector was also mapped and key actors were interviewed, both to indicate levels of activity for each technology and to generate contacts for further information and Case Study identification later in the assignment.

The literature review and stakeholder mapping together provided evidence for the process of technology prioritisation based on:

1. current level of deployment in Newly Industrialised Countries and SSA;
2. appropriateness for SSA in terms of technological sophistication, infrastructure requirements and social workability;
3. replication potential, based on adaptability to diverse contexts and feedstocks;
4. competitiveness with other options for delivering the same energy; and
5. opportunities for innovation, with potential for research to catalyse transformational change.

Geographic screening was also carried out and SSA countries were scored against 12 factors to identify those with the most conducive commercial environments, highest indications of bioenergy demand, levels of sector interest and greatest potential for impact and reach.

3.2 Findings

3.2.1 Academic literature

The systematic review of academic literature generated 6,020 published articles for the eight primary conversion technologies. Anaerobic digestion achieved the highest article count, followed by gasification, direct combustion and fast pyrolysis. Slow pyrolysis, though widely used in charcoal-making in SSA, featured low in volume of literature. Of the bio-chemical pathways, microalgae and liquid biofuels from ethanol registered fewer than a quarter of the number of articles of anaerobic digestion. Oil pressing and butanol registered the lowest count.

Africa featured higher in articles about slow pyrolysis than any other technology, reflecting research interest linked to charcoal. A smaller percentage of articles with an SSA focus were found across the other technology types. Low rates of non-technical articles (indicating higher commercial development) were recorded for liquid biofuels.

Analysis of feedstock mentions revealed that thermo-chemical technologies (such as direct combustion and slow pyrolysis) are skewed towards woody biomass, while liquid biofuel technologies (such as fermentation and oil pressing) rely on agro-fuels. The most feedstock-flexible technologies according to the literature are fast pyrolysis, gasification and anaerobic digestion, though each might need to be adapted for specific feedstocks.

In summary, gasification and anaerobic digestion emerged from the academic literature as the technologies attracting most research interest, followed by direct combustion and microalgae.

3.2.2 Non-academic literature

Direct combustion for heat is the dominant biomass processing 'technology' worldwide. There are various sub-5 MW examples in industries in SSA such as sugar, tea and forestry. Given that the technology is not sophisticated and can use multiple feedstocks, it is deemed appropriate, replicable and competitive for SSA, but with relatively low potential for innovation it has limited value within the BSEAA context.

Steam turbines can be used for electricity generation and industrial CHP above 100 kW. There is high potential in industries with lignocellulosic waste such as sugar, tea and pulp and paper. South African companies manufacture suitable equipment. These systems take a relatively long time to start up, however, and can be costly to maintain, making the technology better suited to small industries than community installations. The technology has high replication potential and there may be innovation opportunities in developing off-the-shelf units from 250 kW to 5 MW.

Steam engines have existed since the industrial revolution but there are few manufacturers producing low power units. The sophistication level is lower than steam turbines and existing projects in SSA are at smaller capacities. Steam engines can be started up quickly and operate at lower load factors than turbines, with lower investment and maintenance costs (but still considerable compared to diesel generator sets). The technology has high replication potential as it can use numerous feedstocks. There are potential opportunities for innovation in manufacturing off-the-shelf units for community use and light industrial applications.

Stirling engines are indirectly-fired gas engines and models for power and CHP exist from 1 kW_e to over 100 kW_e. The external heat may come from any source, though no biomass-fuelled examples are known in SSA. Given that the technology is not widely available, even in Europe and the US, appropriateness for SSA is considered to be low. Stirling engines are also less competitive than other combustion-based systems due, for instance, to the need for special materials in the heat exchanger. With an absence of current SSA activity it is unrealistic to expect commercial penetration.

Organic Rankine Cycle (ORC) systems use waste heat to produce electricity via turbines. Several European and US companies offer systems that can operate from biomass heat, although the ORC projects identified in SSA use geothermal sources or iron smelting. Opportunities exist to explore cost reduction and adaptation to SSA, but a lack of working models and a high level of sophistication limit its potential.

Gasification: Gasification entails heating a feedstock to produce gases that react to form syngas, which can (co-)fuel an internal combustion engine for electricity or meet heating and cooling needs. Efficiency should be higher than biomass combustion at small scale, and small gasification plants for power and heat are seen in India from 30-150 kW_e. Scattered demonstration projects exist in SSA. The technology is more sophisticated than direct combustion and requires skilled maintenance. Gas cleaning is crucial to avoid engine damage, but is expensive and produces carcinogenic waste. Gasification systems can be designed for a range of feedstocks, making them suitable for diverse applications to serve a mini-grid or industrial load. There is opportunity for innovation in gas cleaning, including reduction of water use and toxic effluents.

Fast pyrolysis produces bio-oil that can be used to generate heat or electricity, for example through a boiler and steam turbine or in a diesel engine. There are several companies in Europe and North America with early commercial technologies planned in the range 20-40 Ml/yr, but fast pyrolysis is technically challenging and not yet deployed at scale due mainly to instability and high acidity of the bio-oil and technical difficulties associated with certain feedstocks.

Slow pyrolysis is widely used in SSA's charcoal industry but the capture of waste gases from centralised charcoal-making to produce electricity or heat has not been seen. There are companies in Brazil and France exploring this approach, but the dispersed nature of charcoal making in SSA limits transferability. The concept offers opportunities for technological innovation, but requires fundamental changes to the way the entire charcoal industry is configured that lie outside the scope of BSEAA.

Seed oil for internal combustion engine: After filtering, seed oil can be fed to diesel engines to power generators or pumps. Projects from a few kW to over 100 kW exist in SSA using jatropha, croton, castor or palm oil. Direct use of the oil may require regular cleaning of injectors. Evidence from pilots suggests that quality, availability and cost of feedstock in comparison with diesel is a major challenge. Although many jatropha oil projects sprung up in the early 2000s, most failed because yields were lower than anticipated. There is some innovation potential, especially in oil quality improvement to reduce engine damage. Competitiveness with other energy sources is questionable, however.

Seed oil for transesterification, a process in which the oil reacts with methanol or ethanol in the presence of potassium or sodium hydroxide to form biodiesel. Palm, jatropha and croton oils have been used as feedstock in SSA, but projects tend to be >10 Ml/yr. Methanol is only produced in South Africa and its importation increases costs. The low price of fossil fuel means that the process is unlikely to be competitive within the BSEAAA time horizon.

Anaerobic digestion for direct use: Community biogas projects are technically understood and feedstock flexibility is high. The challenge to implementation is organisational, given the need for multiple families to cooperate in feedstock supply and gas sharing. Anaerobic digestion for community use would be highly challenging and no examples are known (except in institutions).

Anaerobic digestion for internal combustion engine: Biogas can power engines to produce mechanical energy for direct use, to generate electricity or for heating or cooling. In SSA there is growing interest in using processing wastes from sisal, flowers, vegetables, tanneries and slaughterhouses from 150 kW_e to 5 MW_e. The concept is appropriate given relatively low sophistication and feedstock flexibility. Biogas can provide electricity at lower cost than grid or generator electricity if feedstock is available *in situ*. There is scope for innovation on feedstocks, microbes and applications.

Ethanol fermentation: Ethanol can be produced from starch- or sugar-rich crops in both hydrous form (usually for cooking) and anhydrous form (for blending with gasoline). Only three ethanol production projects could be found in SSA <10 Ml/yr, the most interesting being a Brazilian micro-distillery initiative in Nigeria. Feedstocks such as cassava, sugarcane or sweet sorghum are available in a range of SSA countries. Micro-distilleries require secure feedstock supply, however, and this can be challenging. The lower energy content of ethanol and its higher price compared to other fuels also represent an economic challenge for ethanol-based cooking fuels. Innovation will lie in proving micro-distillery technology and the supply chain concept.

Butanol fermentation: Butanol is produced by fermentation from starch or sugars. It is in theory more appropriate for cooking than ethanol as its energy content is higher, but there are no pilots in SSA from which to draw experiences.

Microalgae: Microalgae are photosynthetic microorganisms that can produce lipid-rich biomass. Research on algal energy in SSA is dominated by South African universities, with a focus on project feasibility and identification of suitable strains. Algae-to-energy does not appear appropriate for SSA in the short- to medium-term as production systems are technically complex and require large scale operations.

3.3 Technology Prioritisation

A comparison of the 15 technology combinations based on the review of non-academic literature produced a set of composite scores (Table 4).

Table 4. Technology favourability scores

Primary conversion technology	Secondary Conversion technology	Level of activity	Appropriateness for SSA	Replication potential	Competitiveness	Opportunities for innovation	***Total***
Combustion	None	3	3	3	3	1	***13***
	Steam turbine	3	2	3	3	2	***13***
	Steam engine	1	2	3	2	2	***10***
	Stirling engine	1	1	3	2	3	***10***
	ORC	1	1	3	2	2	***9***
Gasification	Internal combustion engine	2	2	3	2	3	***12***
Fast pyrolysis	Combustion	1	1	2	1	2	***7***
Slow Pyrolysis	Internal combustion engine	1	1	3	1	1	***7***
Oil pressing	Internal combustion engine	2	2	2	1	2	***9***
	Transesterification	1	1	2	1	1	***6***
Anaerobic digestion	None	1	1	3	1	1	***7***
	Internal combustion engine	2	2	3	2	3	***12***
Fermentation	Ethanol fermentation	2	2	2	1	2	***9***
	Butanol fermentation	0	1	1	1	2	***5***
Microalgae		1	1	2	1	3	***8***

The highest-scoring technology combinations were those based on combustion, gasification and anaerobic digestion, reinforcing the findings of the academic literature review. Direct combustion-to-heat has been so widely employed for so long, however, that it lacks significant innovation potential. It was therefore recommended that the following three technologies should be adopted for more in-depth investigation in the TVC Prioritisation stage:

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

3.4 Country shortlisting

On the basis of combined scoring across 12 enabling factors, the following ten countries were recommended for inclusion in the remaining phases of the study:

East Africa	West Africa	Southern Africa
Ethiopia	Ghana	Mozambique
Kenya	Nigeria	South Africa
Tanzania		Zambia
Rwanda		
Uganda		

Those excluded were high risk investment destinations or countries of recent conflict (DR Congo, Liberia, Sierra Leone, Somalia, South Sudan and Sudan), along with Malawi and Zimbabwe (which ranked low for rule of law, corruption and market potential).

3.5 Stakeholder mapping

The stakeholder mapping exercise covered multilateral energy initiatives, UN agencies, technical, advisory and capacity-building projects, small grant funds, multilateral and bilateral bank projects, and specific UK-funded initiatives. Investment facilities in the private sector were also researched. Privately-funded examples of bioenergy technology in SSA at mid-scale are few in number, reinforcing the need to investigate why this may be the case to unlock opportunities.

The academic landscape around bioenergy technology in SSA was found to be dominated by South African institutions, with hubs also in Kenya, Ghana, Tanzania, Nigeria and Malawi. Outside SSA, prominent European universities are conducting research on various facets of bioenergy, with some working directly in SSA. Brazil has strong research capacity in liquid biofuels and institutional expertise was also noted in India and the Philippines. Leading private sector project developers and technology providers active in SSA were also profiled for the prioritised technologies.

3.6 Next steps

With client approval, the team was now ready to investigate feedstocks, end uses and enabling conditions in more depth for the three proposed technologies and ten priority countries. Case studies were then to be selected that would provide examples from which to draw experiences and lessons on barriers and opportunities.

4. Technology Value Chain Prioritisation

4.1 Introduction

The study team had now identified ten promising countries and three bioenergy technologies for more in-depth investigation:

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

During February and March 2017, the next phase prioritised particular TVCs that combined these technologies with particular feedstocks and end uses, with potential for replication. The subsequent phase would then explore those TVCs in more depth through a case study approach, in order to identify specific opportunities for research-led innovation.

4.2 Approach

The team decided to base the analysis on those TVCs for which there had been at least one operational example in SSA, successful or otherwise. It was therefore agreed that a shortlisted TVC for each technology should have been attempted in at least one verifiable project in SSA within the last decade (above household scale but below the agreed 5 MW threshold) and should ideally also offer evidence of success outside Africa. Systematic web searches were carried out to identify such qualifying examples for each technology across 29 English and French-speaking countries in SSA and six Newly Industrialised Countries. A parallel investigation was undertaken of project developers, technology providers, energy initiatives, research organisations and funding agencies to triangulate information. Technical and operational details were verified through direct contact with nearly 70 individuals.

4.3 Findings

The research generated a database of 153 TVC examples in SSA, though fewer than 100 installations had actually been constructed and a majority were no longer believed to be functioning, especially among the gasification projects. At the scale of 10 kW to 5 MW, 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 most often supported by donor-funded grant programmes.

4.3.1 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. Just 12 were thought to be functioning and a similar number with unclear status were also potentially operational. Energy output is split roughly equally between large (>1 MW_e), medium (0.1-1 MW_e) and small (<100 kW_e) installations. The functional projects are all located in abattoirs, 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_e, 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 in SSA using abattoir waste, with examples from 30 kW_e to over 275 kW_e in Uganda, 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 rather than refrigeration as intended.

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

The remaining examples of anaerobic digestion operate using agricultural wastes. The largest and most successful are in Kenya, including a 2.8 MW_e system using vegetable processing waste, a 160 kW_e/170 kW_{th} plant using mainly spent tea and a 445 kW_e system using avocado processing by-products. Other agri-businesses have invested at scattered sites, including a 1.2 MW_e plant in Gabon using palm oil mill effluent, a 300 kW_e 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 and the other using fruit processing waste.

There has meanwhile been rapid growth of anaerobic digestion in several **Newly Industrialised Countries** including India, Thailand, Indonesia, the Philippines and Brazil. 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 commercial developers may find less attractive.

In summary, anaerobic digestion is a well-developed technology that has been widely adopted globally for C(C)HP. 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 digestate themselves. There may be innovation potential around the development of cheaper and more durable materials for digesters, 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 identified, 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 mid-sized farms and industries.

4.3.2 Gasification

47 examples were identified in SSA of gasifiers powering internal combustion engines 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, however, and four of these - two in Uganda, one in Benin and one in Nigeria - operate only intermittently. Two in Ghana have only operated 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 using agricultural by-products, just three are thought to be 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 oil palm kernel shells, 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 intended to 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, 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.

Within **Newly Industrialised Countries**, small-scale biomass gasification has been introduced 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 major 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.

In summary, 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. Performance is hampered by lack of technical capacity, stringent feedstock requirements, high tar content of the syngas and contamination of cleaning water. 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 could not be verified prior to the field visits (see chapter 5.3.2). 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.

4.3.3 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, of which one (a 640 kW_e plant in Côte d'Ivoire) is fed with palm oil waste, while the others are 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_e steam turbine plant fuelled with sawmill waste is planned in Cameroon and a larger (6 MW_e) 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_e 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.

In 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_e 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 was agreed for the next phase, in order to investigate opportunities for further uptake in agricultural, agro-industrial and forestry industries in the sub-1 MW_e range. The technology is thought to be inefficient for power-only generation at these small scales, so there would need to be demands for cogeneration.

4.4 Conclusion and next steps

Anaerobic digestion was deemed 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), despatchability 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. It was agreed instead that desk research would 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 were to be selected to provide working examples of the prioritised TVCs from which to draw experiences and lessons. These would be described in Case Study Reports identifying the main barriers and opportunities for replication and innovation, and giving an indication of research areas that DFID might usefully support in future.

5. Technology Country Case Studies

5.1 Introduction

The iterative phases of literature review, stakeholder mapping and technology value chain prioritisation led to the shortlisting of anaerobic digestion, gasification and combustion-based steam turbines as the most promising bioenergy technologies for BSEAA-supported research and innovation. During the Case Study phase (April to July 2017), a sample of representative installations was visited and desk research was conducted on steam turbines for heat or power production at sub-1 MW scale. A comprehensive Case Study Report drew upon these experiences to highlight the main barriers and opportunities for wider adoption of anaerobic digestion, gasification and small-scale steam turbines in SSA, in order to guide potential research themes for future DFID support.

5.2 Approach

From a database of 153 anaerobic digestion and gasification projects in SSA, a sample of Case Studies with heat and/or power output between 10 kW_e and 5 MW_e was selected based on location in priority countries, current or recent operation, operator welcome and accessibility. Visits were organised to 18 qualifying sites in seven countries, comprising 12 biogas plants (mostly in the 100-500 kW_e range) and six gasifiers (mostly at smaller scale around 30 kW_e). Applying a standard information checklist, the aim at each site was to identify barriers to replication that DFID-supported research could potentially help address. Each visit resulted in an illustrated Case Study Report and these form an important part of the supporting analysis.

The country visits gave an opportunity to meet local experts to gather contextual information and supporting opinions. Team members also attended the ECOWAS/GBEP Bioenergy Week in Ghana, a consultative meeting with the German Biogas Association in Munich and the World Biogas Expo in Birmingham.

No small-size biomass-based steam turbine plants could be identified, so site visits were not possible. Parallel desk research was instead carried out into sub-1 MW steam turbines to identify potential research and innovation opportunities.

5.3 Identified Barriers

5.3.1 Anaerobic digestion

Three of the profiled biogas projects can be deemed technically and commercially successful, showing that such ventures *can* be developed and operated in SSA if the conditions are right. The barriers experienced by developers fall into six categories.

Barrier 1: Unreliable feedstock supply

All of the successful biogas projects have sufficient feedstock on-site as a by-product of the developer's own business or an adjacent business with an equity stake. There was no successful example where the primary feedstock was being brought in from elsewhere. Novel feedstocks (e.g. lignocellulosic materials or dryland plants) may represent a breakthrough in expanding the range of feedstock options for SSA.

Barrier 2: Costly and insufficiently adapted technology

The high cost of European and North American biogas systems is a barrier to investment in SSA. Technology transferred without modification may also prove inappropriate for local operating conditions. For replication beyond well-resourced agribusinesses, cheaper designs are needed – potentially from Newly Industrialised Countries - that are adapted to the local context.

Barrier 3: Limited operator technical capacity

Insufficient operator capacity has in some cases led to technical problems such as incorrect substrate temperature, pH, solids content or microbiological conditions. Systems have under-performed or broken down as a result. There is a need to elevate skill levels through training and operational exposure.

Barrier 4: Lack of viable business models

A number of factors are resulting in unviable business models. Besides insecurity of feedstock supply, they include reliance on a sole income stream, which is rarely a viable biogas strategy in SSA; and insufficient financial engagement of project owners resulting in commercially unrealistic models. Projects fully funded by donor grants have encountered viability problems. There is a need to prioritise sites that allow valorisation of multiple outputs. Given also the lack of commercial financing for biogas in SSA, donor resources need to be applied more strategically.

Barrier 5: Unfavourable policy and regulation

Most early developers of biogas projects target captive heat and power demand within agri-businesses. Replication beyond captive sites requires a supportive framework of government incentives, such as attractive feed-in tariffs and fair access to the grid.

In many SSA countries, environmental regulations are not enforced and polluters may face no penalties for waste dumping. This makes investment in biogas less economically attractive as a waste clean-up technology.

Barrier 6: Limited access to manufacturer support and spare parts

Only one European biogas technology provider has permanent representation in SSA, so plant managers must usually be self-contained with their own in-house personnel. Lack of local support and poor access to spare parts dis-incentivises further uptake of the technology.

5.3.2 Gasification

The developers of the six profiled gasification projects have encountered significant barriers that make replication very challenging. The four community-based plants have been mothballed due to poor commercial viability or technical problems, the fifth is dormant due to lack of feedstock and the sixth has yet to be commissioned due to gas cleaning problems.

Barrier 1: Feedstock quality and availability constraints

Sensitivity to feedstock specifications means that gasification is an inflexible technology, which limits the potential feedstock range and supply-side adaptability.

Barrier 2: Technology limitations

Operating parameters must adhere to precise manufacturer specifications, otherwise high outputs of char, tar and particulate matter may cause cleaning problems, result in engine failure and generate an excess of toxic by-products. Small-scale gasification also lacks the same degree of power despatchability as other energy technologies, requiring a gas storage system or battery bank.

Barrier 3: Lack of viable business models

Anchor customers are often absent from the profiled project, none valorise heat or char; and all were financed to some extent with donor funds. These factors have resulted in commercially unrealistic models and have often led to over-sized systems.

Barrier 4: Limited operator technical capacity

It is challenging to secure the skills required to operate gasification systems in rural locations. There are few qualified individuals who can operate and maintain them successfully, compounding the problem of reliability and reputation.

Barrier 5: Poor access to manufacturer support and spare parts

All gasification equipment is imported to Africa and only one supplier is represented on the continent, resulting in limited access to technical support or spares. The absence of technical back-up further degrades the reputation of gasification.

5.3.3 Sub-1 MW steam turbines

The study confirmed the poor efficiency of steam turbines compared to alternative technologies at sub-1 MW output levels, for inherent technical reasons. There may still be opportunities to retrofit steam turbines for CHP in agri-businesses with an existing heat generation system and significant electricity demand in countries with high electricity costs (e.g. Kenya, Rwanda and Ghana)

5.4 Potential opportunities for DFID support

Future research supported by DFID is expected to respond to the identified challenges facing the deployment of bioenergy in SSA by identifying, testing and piloting appropriate solutions. It is understood that the emphasis will be on those barriers for which research can offer particular value over other types of intervention, and that research which addresses technological barriers will be prioritised.

In defining the limits of any future research in this area, the team proposes a focus on **anaerobic digestion**. The Case Study phase confirmed the growing commercial investment in SSA's biogas sector, which DFID could support through targeted research. The technology has high adoption levels outside Africa from which to draw lessons and leapfrog technologically, and offers significant feedstock flexibility across diverse waste streams, despatchability of the energy produced and co-benefits from environmentally beneficial waste disposal and fertilizer production. Realising the benefits of anaerobic digestion in SSA requires, however, some of the barriers identified through this work to be overcome. Targeted research (examples of which are suggested in 6.2 below) could make a contribution and support further investment in anaerobic digestion in SSA.

It was meanwhile noted in the TVC Prioritisation Report that **gasification** has a poor track record at small output scales and that state of the art systems are complex to maintain, while simpler technologies are proving to be polluting and unreliable. Failure rates in SSA are close to 100% due to problems with gas quality, lack of operator expertise and spare parts, and absence of economic viability. Case study research into the small number of plants in SSA confirmed this discouraging prognosis. The barriers to replication, especially in small-scale community settings, are so significant and wide-ranging that there is no realistic opportunity for research to make a difference to replication potential, and it is not proposed that gasification-related research is supported by DFID.

Desk research into the technical and economic feasibility of sub-1 MW heat or power applications from **steam turbines** reveals potential for retrofitting for CHP at plants with a functioning heat generation system and significant electricity demand. Further feasibility research on this theme is a supplementary option for DFID support.

6. Project completion and handover

6.1 Introduction

Successive phases of BSEAA Phase I research led to the conclusion that anaerobic digestion is the bioenergy technology that offers the greatest potential for replication in SSA at the sub-5 MW output scale, supported by evidence from successfully operating projects.

The barriers facing gasification are meanwhile too significant and wide-ranging for research to make a significant difference to uptake. Gasification-related research is therefore not deemed appropriate for further DFID support.

It is for DFID to decide if further feasibility research into the retrofitting of sub-1 MW steam turbines for CHP to existing (agro-)industrial plants in Ghana, Kenya and Rwanda represents a viable option for future research, balancing the inevitable dilution of resources against the benefits of exploring this lesser opportunity.

6.2 Potential research themes

Assuming a focus on anaerobic digestion, examples of potentially relevant research themes[2] to address the identified barriers are offered below. DFID may also wish to focus on a sub-set of the barriers in framing any future research, to maximise the impact of available resources.

Barrier 1: Unreliable feedstock supply

Investigation into biomass resources across the prioritised BSEAA countries to quantify available feedstocks by identifying concentrated sources under clear ownership, evaluate suitability (including combinations where available) and elaborate business models for their application in biogas systems. Feedstocks could include by-products from agriculture, agro-industry, livestock and municipal waste systems, as well as wild-harvested biomass, and might be seasonal. Such research could build on existing resource studies for specific African countries.

Exploration of the biogas productivity potential of novel feedstocks and feedstock blends, particularly those unique to Africa. Biomass from marginal drylands could be particularly interesting, including crassulacean acid metabolism (CAM) plants. Social and environmental implications would need to be considered, including potential competition with existing uses and food production.

[2] There are also numerous non-research interventions that could address the identified barriers, but we understand that these fall outside the scope of DFID's current interest under BSEAA.

Technical and commercial feasibility assessment of methods for breaking down lignocellulosic feedstocks for anaerobic digestion, to expand the volumes of biomass potentially available for use in African biogas systems and increase biogas yields (taking into account competing uses and values).

Barrier 2: Costly and insufficiently adapted technology

Development of modified versions of European biogas technology to achieve cost reduction through design adaptation, while retaining functionality and reliability, to increase affordability and adoption rates in SSA. This should include customisation to suit African regional climates, seasonality differences, feedstock variation and other operating realities, to increase appropriateness and performance. Standardised African plant designs may result for particular feedstocks and operating environments.

Barrier 3: Limited operator technical capacity

Research into structures that could enhance interaction and mutual support between biogas plant operators, to establish a core of technical expertise for operating modern industrial biogas systems in SSA, building on experiences from other sectors. This could be linked to research into current training provisions within academic, vocational and technical institutions, with recommendations on how to develop a more industry-relevant system for developing operating and maintenance capacity.

Barrier 4: Lack of viable business models

Development of a financial modelling tool for evaluating potential biogas projects at new sites in SSA, in which multiple income streams (including electricity, heat, fertilizer and waste disposal) can be valorised to explore the commercial potential of different models. This could extend to exploring financing opportunities to bring promising opportunities closer to realisation.

Research into models of donor support for the biogas sector that ensure commitment of project developers to commercial success, with meaningful sharing of risk, and ways to maximise community or pro-poor impact.

Development of creative approaches for increasing commercial lending to biogas projects, drawing on successful financing models from other sectors, and including partnerships between development agencies and financial institutions to de-risk lending. Cooperation with initiatives such as PFAN or the Finance Catalyst of RECP is suggested.

Barrier 5: Unfavourable policy and regulation

Financial modelling to explore the impact of different policy measures on a range of biogas configurations, considering various heat and digestate valorisation scenarios, to help guide policymakers towards realistic regulatory and tariff structures (e.g. for electricity grid feed-in) that will support growth of the industry. This could include modelling of the implications of effective enforcement of environmental regulations on the commercial case for biogas projects in SSA.

Barrier 6: Limited access to manufacturer support and spare parts

Advocacy-oriented research into the social, economic and environmental case for governments to support the development of a biogas industry in SSA countries, including co-benefits of waste disposal, fertilizer production, industrial development and job creation, to create a supportive environment for industry to invest and thus increase the access to manufacturer support and spare parts.

6.3 Handover to TEA programme

The study team will ensure that the written outputs of the Phase I research are duly handed over to the TEA Programme management. Core team members from LTS and E4tech will meet with the TEA programme Managing Agent to ensure that the richness and intent of the analysis is also conveyed verbally.

Any further research in this area could potentially involve a range of delivery methods including forming a partnership with industry. Cooperation with other donor-funded programmes would be valuable to maximise effectiveness and reach.