Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Demand Sector Report 7: Sisal Processing
Focus Country: Kenya

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NIRAS LTS INTERNATIONAL

Aston University Birmingham

E4tech Strategic thinking in sustainable energy

AIGUASOL

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Cover photo: Sisal decortication at Kilifi Plantations Ltd, Kenya (credit: Matthew Owen)

NIRAS-LTS International Ltd
Pentlands Science Park, Bush Loan
Penicuik
EH26 0PL
United Kingdom

+44 (0)131 440 5500

mail@ltsi.co.uk

@LTS_Int

www.ltsi.co.uk

Registered in Scotland Number 100833

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EXECUTIVE SUMMARY

NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to research the opportunities and constraints for bioenergy development in sub-Saharan Africa (SSA) across seven shortlisted industries, through five interlinked themes: biomass resources, technology, economic competitiveness, commercial viability and institutional, market and regulatory frameworks. This report, the seventh in the series, focuses on the bioenergy opportunities in the sisal processing sector in Kenya.

Kenya is the world's third largest sisal producer, producing about 25,000 t of sisal fibre per year, of which 95% comes from ten large estates. AD based on sisal processing residues can be used to generate electricity and ensure safe waste management. However, only one estate in Kenya, Kilifi Plantations Ltd. (KPL), has invested in AD for biogas-based electricity generation.

Resource assessments indicate that sisal processing residues, mainly in the form of moisture-rich pulp from the decortication process, are plentiful, readily accessible, lack competing uses and present a waste management problem for processors, making them an ideal feedstock for AD-based electricity generation. There are also opportunities to valorise the AD digestate as a fertiliser.

However, technology is a significant constraint to the wider adoption of AD in Kenya's sisal sector. Most of the European technology providers who have supplied AD equipment to African clients, including to two sisal processors in East Africa, have installed only one plant, indicating a small and immature market for this technology. A lack of diverse, Africa-focused commercial experience, and the absence of local supply chains for equipment, servicing and spares, means that other potential developers lack confidence in the reliability and performance of sisal-based AD systems. The high cost of turnkey European systems is a further deterrent to investment.

An economic assessment of KPL's AD plant indicates that the cost of electricity from the plant is currently higher than that of electricity from the grid. Technical challenges linked to a power factor penalty applied by Kenya Power (the national utility), together with the inability of small-scale generators to access feed in-tariffs (FiT) and the low rates of those FiTs, deter the project's owners from utilising all their available waste to maximise power production. The commercial case for replication of the Kilifi venture based only on avoided costs of sisal waste disposal and the opportunity to meet onsite electricity requirements is weak. There are cheaper forms of waste treatment available to sisal estates. Economic viability depends on the ability to feed surplus power into the grid at viable tariffs. This is currently not possible due to a lack of interest in electricity procurement from biomass-based bioenergy on the part of Kenya Power, resulting in technical and regulatory barriers and unattractive FiTs that make investment in bio-electricity from sisal financially unviable.

In sum, while sisal estates have abundant residues suitable for AD and internal demands for electricity that could be met using biogas-based power generation, adoption of AD in the sector requires lower equipment costs from locally adapted technologies alongside stronger policy and regulatory support to deliver more attractive FiTs, strengthen the grid in rural areas to offtake electricity from small power producers and fully enforce waste treatment and disposal regulations.

Contents

LIST OF ACRONYMS

ABEX	abandonment expenditure
AD	anaerobic digestion
BPH	Biogas Power Holdings
BSEAA	Bioenergy for Sustainable Local Energy Services and Energy Access in Africa
CAPEX	capital expenditure
CHP	combined heat and power
EPRA	Energy & Petroleum Regulatory Authority
ESIA	Environmental and Social Impact Assessment
FCD	Fibre Crops Directorate
FiT	Feed-in-Tariff
G&I	Gender and Inclusion
IPP	Independent Power Producer
JV	Joint Venture
KES	Kenyan Shilling
KPL	Kilifi Plantations Ltd
KPLC	Kenya Power and Lighting Company (Kenya Power)
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
MCA	Multi-Criteria Analysis
MEB	Mass-Energy Balance
MoE	Ministry of Energy
NEMA	National Environment Management Authority
OPEX	operational expenditure
PPA	Power Purchase Agreement
RED	Renewable Energy Directorate (of the MoE)
SSA	Sub-Saharan Africa
TEA	Transforming Energy Access
USD	United States Dollar

1 INTRODUCTION

NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to implement a 2-year project - 'Bioenergy for Sustainable Local Energy Services and Energy Access in Africa-Phase 2' (BSEAA2). BSEAA2 was part of the Transforming Energy Access (TEA) programme, which is funded with UK aid from the UK government. TEA is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition. TEA works via partnerships to support emerging clean energy generation technologies, productive appliances, smart networks, energy storage and more. It increases access to clean, modern energy services for people and enterprises in sub-Saharan Africa (SSA) and South Asia, improving their lives, creating jobs and boosting green economic opportunities.

BSEAA2 was intended to identify and support the development of innovative, commercial bioenergy pathways and technologies to accelerate the adoption of bioenergy in SSA. Building upon BSEAA Phase 1, which took place in 2016/17, the second phase focused on opportunities for the development of anaerobic digestion (AD) and combustion for electricity and/or heat generation in the range 10 kW to 5 MW, with a Technology Readiness Level of 5+. That is, technologies that had been successfully piloted in a representative commercial setting.

The research team investigated the challenges and opportunities affecting the commercial deployment of these technologies in ten focus countries in SSA (Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Rwanda, South Africa, Tanzania, Uganda and Zambia), investigated through six relevant themes: biomass resources, technology, economics, business models, institutional, market and regulatory frameworks, and gender and inclusion (G&I). The research targets bioenergy entrepreneurs, investors and policymakers, aiming to catalyse action for the further development of commercial bioenergy in SSA.

Commercial opportunities and constraints for bioenergy development were assessed within seven shortlisted industries, referred to as 'demand sectors'. These demand sectors and their associated bioenergy pathway and focus countries are presented in Table 1-1. This report, the seventh in the series, focuses on the AD opportunity in the sisal processing industry in Kenya.

Table 1-1. Shortlisted demand sectors for BSEAA2 research

No.	Demand sector	Biomass resource	Technology	Country
1	Cement manufacturing	Biomass residues, part-replacing fossil fuel	Combustion for heat	Nigeria
2	Tea processing	Biomass briquettes, part-replacing fuelwood		Kenya
3	Wood processing	Wood processing residues	Combustion for CHP	Tanzania
4	Palm oil processing	Palm oil mill effluent	AD for CHP	Ghana
5	Horticulture	Fruit & vegetable processing residues		Kenya
6	Dairy	Cattle manure		South Africa
7	**Sisal processing**	**Sisal processing residues**	**AD for electricity**	**Kenya**

2 METHODOLOGY

2.1 OVERALL METHODOLOGY

During a 6-month preliminary assessment (2019-20), the research team screened a range of bioenergy 'pathways' in SSA involving AD or combustion, comprising a specific biomass feedstock, conversion technology, end use and demand sector. The aim was to identify the most promising pathways for the adoption of bioenergy-based combustion or AD across the target countries, for which the existence of at least one operational venture could be verified. This resulted in the shortlisting of the seven priority demand sectors in five countries. During the following 12 months (2020-21), these demand sectors were investigated in detail across the five research themes, to explore the experiences of both adopters and non-adopters of bioenergy technology.

Information was gathered from site visits to representative commercial operations and from other stakeholders active in bioenergy in SSA, from published literature and from partners of the TEA Programme, UK Energy Catalyst and Innovate UK. A bibliography is in Appendix 1 and a list of people consulted is in Appendix 2.

For each Demand Sector, a 'Base Case' and a 'Bioenergy Case' were identified:

- The **Base Case** refers to the industry standard for energy use in the given demand sector in the target country; that is, the default heat, power or combined heat and power (CHP) solution used by a majority of similar businesses.
- The **Bioenergy Case** refers to a specific enterprise (or 'flagship project') that has transitioned to the use of bioenergy for heat and/or electricity generation in the target demand sector, using either combustion or AD.

The Base Case and Bioenergy Case for the sisal processing sector are defined in Table 2.1.

Table 2.1: Base Case and Bioenergy Case for the sisal processing sector

Base Case	Bioenergy Case
Sisal processors meeting all their electricity requirements from the grid	Sisal processors using processing residues to meet part of their electricity requirements from AD **Flagship project: Kilifi Plantations, Kenya**

This report analyses the Bioenergy Case flagship project across the six study themes of biomass resources, technology, economics, commercial viability, governance frameworks and G&I to identify the factors that have enabled the adoption of sustainable bioenergy. The findings are compared with Base Case examples to identify the opportunities and constraints for other enterprises in the same demand sector to adopt similar solutions. Based on this analysis, the potential and requirements for wider adoption of the Bioenergy Case in the chosen demand sector are assessed, both for the target country and for the other BSEAA2 countries.

2.2 INSTITUTIONAL, MARKET AND REGULATORY FRAMEWORK ASSESSMENT

The institutional, market and regulatory framework assessment for AD in Kenya's sisal sector was based on web-accessed reports, journal articles, news reviews and interviews with government, private sector, development partners and NGO informants, which augmented team members' own extensive experience. Consultations took place remotely and in person with representatives of five of Kenya's sisal estates and with the Energy and Petroleum Regulatory Authority, Kenya Power and Lighting Company, the National Environment Management Authority, the Fibre Crops Directorate of the Ministry of Agriculture, Livestock, Fisheries and Co-operatives, and the Renewable Energy Division at the Ministry of Energy, to understand the dynamics of energy and waste management in the industry. Field visits took place to Kilifi Plantations and to Migotiyo Plantations, which provided useful insights into practical experiences and investment options for AD.

2.3 BIOMASS RESOURCE ASSESSMENT

The objective of the resource assessment was to determine resource availability, bioenergy potential, feedstock-technology interface and mass-energy balance (MEB) for the relevant feedstocks in each demand sector, in this case the pulpy residue from sisal processing. Existing data on Kenya's sisal sector was used, adopting biomass feedstock categories from FAO (2004) and IEA & FAO (2017). Country-specific resource potential was calculated based on the quantity of sisal produced, the residue-to-product ratio, the recoverable fraction, the fraction available (considering other uses) and its bioenergy potential (see source data in Appendix 3). An MEB model was also developed, to simulate the energy system using validated performance and efficiency data. Based on the known feedstock inputs of the flagship project, the model quantifies expected material flows and outputs of heat and power under optimised performance conditions, allowing replication potential to be estimated based on the preceding assessment of the biomass resource.

2.4 TECHNOLOGY ASSESSMENT

The objective of the technology assessment was to determine the technological implications of bioenergy use in each demand sector, in this case for generating electricity from sisal residues in Kenya, based on technical considerations and practical experiences at the Bioenergy Case flagship project, Kilifi Plantations Ltd (KPL). KPL is currently the only sisal estate in Kenya to have set up an AD plant to generate electricity to run its processing facility and sell excess power to the grid. Exploring the factory's experiences from a technical perspective and interacting with other sisal estates (such as Teita Estate and Migotiyo Plantations) enabled the team to characterise the current technology and its supply chain landscape, and the opportunities and requirements for replication linked to technology.

2.5 ECONOMIC COMPETITIVENESS ANALYSIS

The objective of the economic analysis was to compare energy costs under the Base Case and the Bioenergy Case, to investigate potential economic drivers for wider adoption of bioenergy in this demand sector. A 10-year discounted cash flow analysis

was carried out using an Excel-based Life-Cycle Cost (LCC) modelling toolkit developed by AIGUASOL (see Appendix 4).[1] The main economic indicator considered was the Levelized Cost of Energy (LCOE), in USD/MWh. LCOE comprises CAPEX (upfront investment and other amortizable costs), OPEX (personnel, consumables and operating costs) and ABEX (abandonment expenditures). For this demand sector, the LCOE was calculated for electricity only. The model was also used to perform sensitivity analyses considering a range of values for relevant input parameters.

2.6 Commercial viability assessment

The objective of this assessment was to determine the commercial case for bioenergy in each demand sector, the factors affecting its successful adoption at the flagship project and the potential for wider uptake in the same sector, based on barriers, enablers, market potential and finance. The Bioenergy Case at KPL was first analysed to identify the requirements for commercial success linked to supply chain ownership, demand for electricity and factors such as waste disposal and financing. Information was obtained from stakeholder interviews, literature review and a site visit. This was followed by an analysis of the wider commercial potential for AD within the sisal sector, analysing barriers and enablers for supplying heat and electricity under various scenarios. Taken together with an assessment of market size and conditions, the barrier analysis gave an indication of wider market potential. Finally, potential sources of finance and their relevance for bioenergy projects such as this were assessed.

2.7 Gender and inclusion assessment

The objective of the gender and inclusion research was to identify G&I-related issues in each demand sector, and to highlight potential areas for improved awareness, inclusion and participation of women. The research framework was adapted from a UNDP (2004) toolkit, and was structured around: access to assets; beliefs and perceptions; practices and participation; and institutional laws and policies. The research focused mainly on the production and supply of feedstocks and, where applicable, the bioenergy conversion process. A literature review was also carried out, and further information was gathered through interviews with informants working in G&I and at the flagship project.

2.8 Multi-Criteria analysis

A multi-criteria analysis (MCA) was carried out to summarise the degree to which each the study's five thematic strands are conducive or detrimental to the adoption of the particular bioenergy solution in each demand sector. Each theme was given an average 'score' from 1 to 10, based on the degree to which various sub-factors under each theme make a positive contribution (high score) or act as an impediment (low score) to the viability of the Bioenergy Case. The MCA results are presented in the concluding chapter as a multi-point spider diagram, to provide a graphical summary of the factors most likely to support or impede successful adoption of bioenergy in the demand sector in question. The input data for the MCA are in Appendix 5.

[1] 10 years is a standardised period chosen for economic analysis based on an averaging of longer periods generally applicable for sustainability assessments and shorter periods applicable for investors consideration, and is not necessarily indicative of the functional lifetime of a particular project.

3 OVERVIEW OF THE SISAL SECTOR

3.1 SECTOR LANDSCAPE

Kenya is the world's third largest sisal producer (Figure 3.1) and is estimated to produce an average of 25,000 t of brushed, baled sisal every year, of which over 90% is exported (Fibre Crops Directorate, 2019; WGC Services, 2020). Sisal grows well on most free-draining soils, including in arid regions unsuitable for many other crops, though has low tolerance to water-logging and salinity (FAO, 2020). It is a perennial crop grown in 12-16 year cycles, with leaf harvesting possible from the second year onwards (FAO, 2020).

The value of Kenya's sisal industry has grown by an average of 5% p.a. since 2005, accelerating to over 7% p.a. today, due to rising global demand for natural and recyclable fibre (ibid.). Kenyan sisal is known for its quality and is used in high-value products such as woven materials, robes, interior design, high quality yarns, construction and car manufacturing (FAO, 2017; Phologolo et al., 2012).

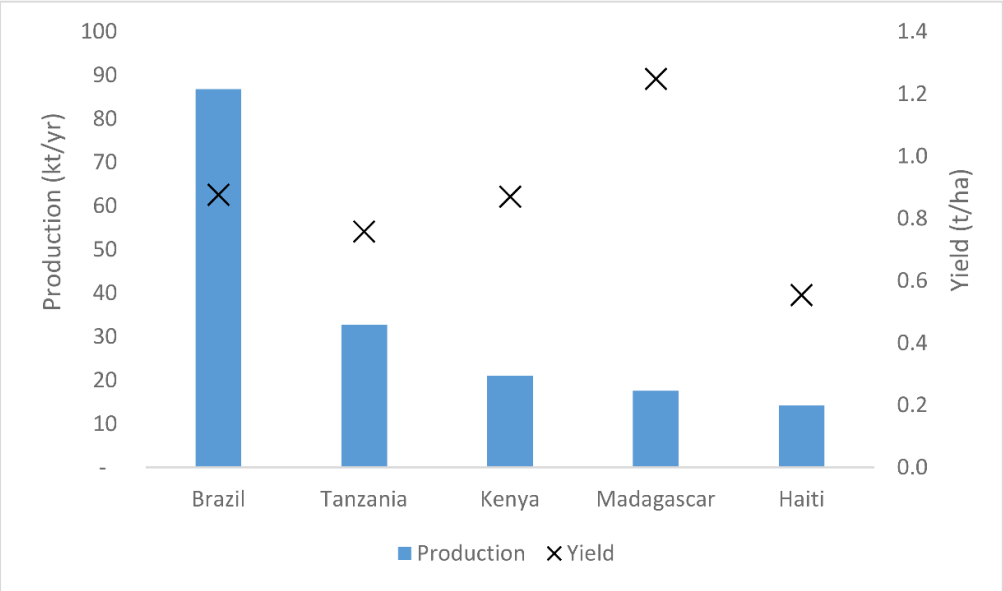

Figure 3.1. Top-5 sisal producers (FAO, 2021)

About 95% of Kenya's sisal comes from ten large estates (Figure 3.2) and the balance from some 10,000 outgrowers and smallholders. The Governent of Kenya, through the Fibre Crops Directorate (FCD) of the Ministry of Agriculture, Livestock, Fisheries and Cooperatives, is putting considerable effort into encouraging more smallholder sisal production.

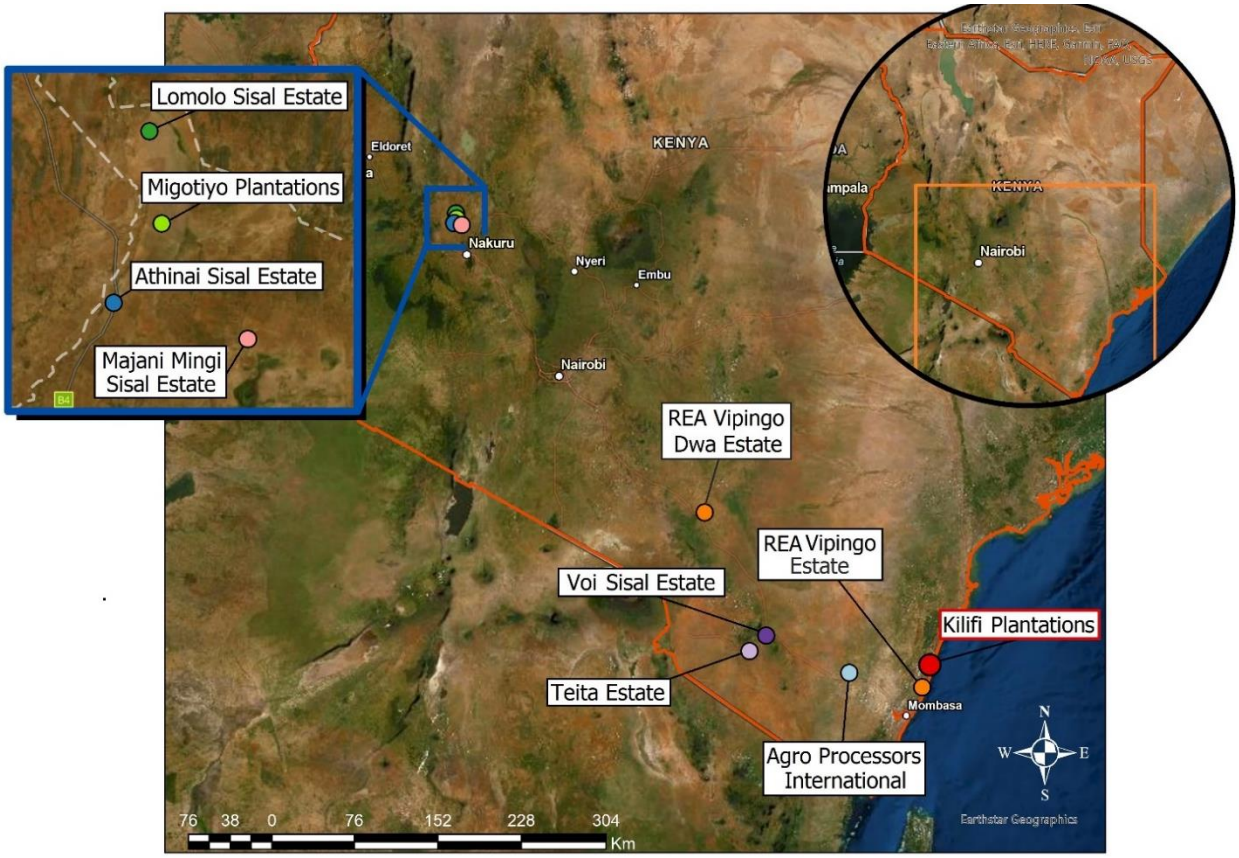

Figure 3.2: Locations of sisal estates in Kenya (Source: authors' compilation)

The plantation areas and sisal output of the ten leading estates for the production year 2019 are summarised in Table 3.1.

Table 3.1. Plantation area and annual output of large sisal estates in Kenya, 2019

Name of estate	County	Plantation area (ha)	Sisal production (t/yr)
1. Teita Estate	Taita Taveta	10,000	7,952
2. REA Vipingo Dwa	Makueni	5,288	6,775
3. REA Vipingo Plantations	Kilifi	3,583	4,334
4. Majani Mingi Sisal Estates	Baringo	688	2,333[2]
5. Lomolo	Baringo	1,356	
6. Athinai Sisal Estate	Nakuru	818	
7. Agro Processors International	Kwale	5,263	2,282
8. Migotiyo Plantations	Baringo	2,400	1,689
9. Kilifi Plantations	Kilifi	380	348
10. Voi Sisal Estate	Taita Taveta	1,924	n/a[3]
		Total:	**25,713**

Sources: K. M. Lubanga, personal communication, 29 September 2020; REA Vipingo (2020)

[2] Processing of sisal from Lomolo, Athinai and Majani Mingi all takes place at Majani Mingi, hence, a consolidated figure for total production from all three estates in the table.
[3] Voi Sisal Estate was not operating in 2019, so has no production data for that year.

3.2 Bioenergy in the sisal sector

Sisal (*Agave sisalana*) is a species of flowering plant native to central America, and now widely cultivated in many tropical regions. Each sisal plant consists of a rosette of thick, fibrous sword-shaped leaves, 1.5–2 m in length. Fibre is extracted from the leaves by a process known as decortication, in which the leaves are crushed and beaten by rotating wheels with blunt knives in a machine known as a corona, to draw out the long fibres. The fibres are washed, dried on outdoor lines and then brushed, graded and baled for sale, while the short fibres and liquid residues, which comprise 96% of the fresh leaf mass, are discarded in the form of a green, moisture-rich pulp.

In the mid-to-late-2000s, there was considerable interest in Kenya in exploring the use of AD to generate electricity from agri-processing residues, including sisal wastes. The residues and effluent from Kenya's sisal processors have the potential to generate more than 20 MW of electricity from AD (Fischer et al., 2010). Environmental legislation on the treatment and disposal of these wastes provides an additional impetus for investment in AD for power production. However, only one sisal processor, Kilifi Plantations Ltd. (KPL), with support from GIZ (Germany), has actually made such as investment.

This demand sector report explores the experiences of KPL with AD for elecricity generation in the sisal sector, as the Bioenergy Case flagship project, and the opportunities and barriers to the wider adoption of this bioenergy technology by other sisal processors in Kenya and the wider region.

3.3 Institutional, regulatory and finance framework

3.3.1 Institutional framework for the sisal sector

The institutional set up for Kenya's sisal sector includes both private sector players and government bodies (Figure 3.3). While the private sector focuses on sisal production, processing and export, government bodies are responsible for licensing, policy, quality assurance, employment regulation and export facilitation.

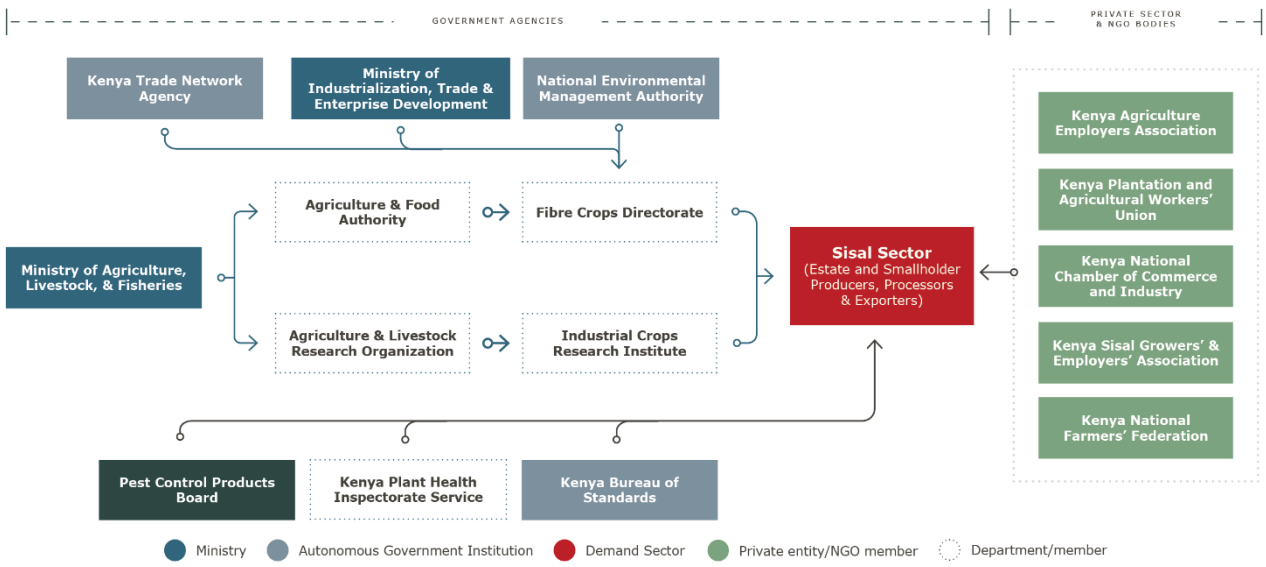

Figure 3.3: Institutional framework for Kenya's sisal sector (Source: authors' compilation)

Every sisal estate is licensed by the FCD, which is the main support and regulatory body for the sector. The Agricultural and Livestock Research Organization and the Industrial Crops Research Institute both provide development and capacity building support. The Kenya Plant Health Inspectorate Service and the Pest Control Products Board are jointly responsible for setting and enforcing regulations and standards on agronomic quality and hygiene, while the Kenya Bureau of Standards has developed standards specific to the horticulture sector, particularly the Sisal Industry Code of Practice (2019), which specifies requirements and recommendations based on good practices in carrying out production, sisal leaf processing, storage, inspection, sisal fibre processing, transportation and marketing of sisal.

The National Environment Management Authority (NEMA) is Kenya's paramount environmental enforcement agency. NEMA has offices in all 47 counties and is responsible for licensing and enforcing regulations concerning air quality, water quality and the management, disposal and utilisation of sisal processing residues.

The Ministry of Industrialization, Trade and Enterprise Development and the Kenya Trade Network Agency are the primary bodies regulating the industrial and commercial aspects of the sisal sector. The Kenya National Chamber of Commerce and Industry is a member-based institution that works to protect the commercial interests of the Kenyan business community, including the sisal sector. It has offices in every county and its membership includes enterprises of all sizes. There are two additional private sector associations relevant to the sisal sector: the Kenya Sisal Growers Association is a loose association of the ten largest growers (Table 3.1), whose main function is to set up the framework for estate owners and estate workers to interact; the Kenya Plantation and Agricultural Workers' Union represents estate employees' rights and interests, primarily in the sisal, cotton, coffee, tea and pyrethrum plantation sectors.

3.3.2 Institutional and regulatory framework for bioenergy in the sisal sector

The institutional set up for energy generation in sisal processing includes bodies from both the environment and energy sectors (Figure 3.4). NEMA is responsible for enforcing environmental regulations (in this case on the safe management of sisal processing wastes) and ensuring that environmental impacts of any new developments are assessed and mitigated. Energy sector bodies**,** namely the Ministry of Energy (MoE), the Energy & Petroleum Regulatory Authority (EPRA), the Kenya Power and Lighting Company (KPLC or Kenya Power) and the Rural Electrification and Renewable Energy Corporation, working with the MoE's Rural Energy Directorate (RED), define the framework for bioenergy (particularly electricity) generation, sales, prices, power purchase agreements and tariffs (particularly feed-in-tariffs).

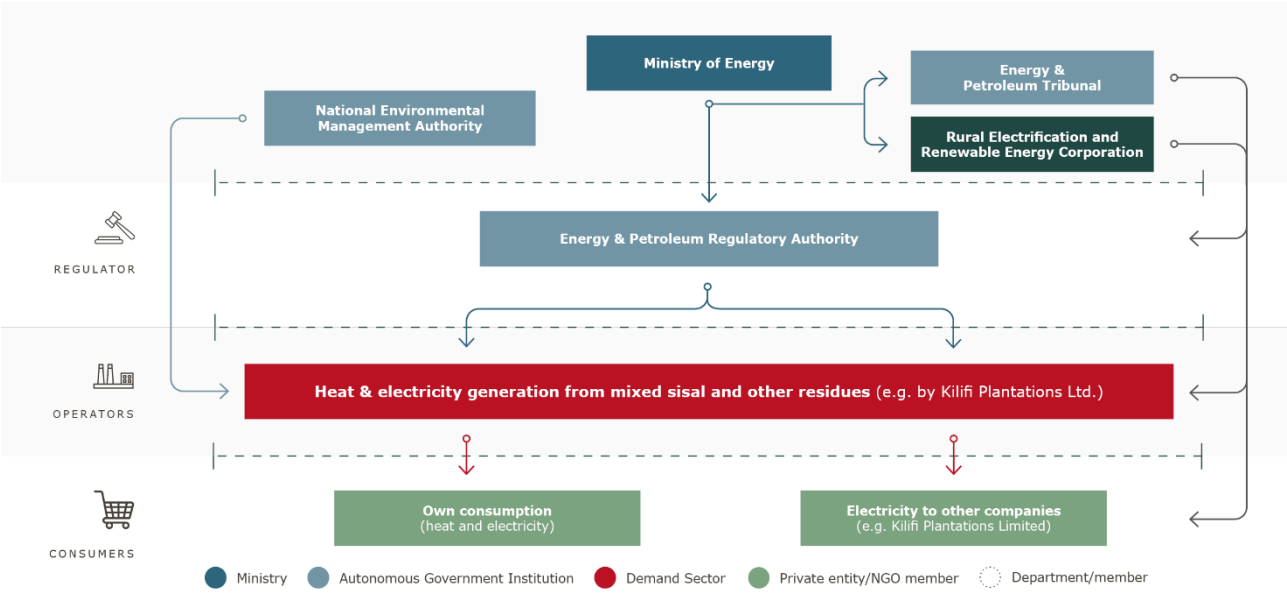

Figure 3.4. Institutional and regulatory framework for energy in Kenya's sisal sector (Source: authors' compilation)

Several policy and regulatory areas relate to the use of wastes from sisal processing, including generating electricity and compressed biogas for own use and for sale. Most of these policies are set and enforced at a national level by the MoE and the EPRA.

The EPRA is responsible for regulating electricity (and the use of biogas for energy). Generating biogas for self-consumption and/or sale to other parties requires an EPRA-led 'Team Assessment' involving the EPRA, NEMA, the Kenya Bureau of Standards and relevant county or municipal authorities, with a focus on safety.

The RED is responsible for renewable electricity policy formulation, review, planning, promotion, development, and monitoring and evaluation of biogas electricity generation support through applicable feed-in tariffs (FiTs). It sets eligibility of bioenergy (including biogas) projects generating between 200 kW and 10 MW of electricity. Kenya Power is the off-taker from all power generators on the basis of negotiated Power Purchase Agreements (PPAs).

A new Bioenergy Strategy for 2020-2027 (Ministry of Energy, 2020) was released in late-2020. The strategy was developed by high-level experts from various ministries, supported by GIZ, the World Bank, ICRAF and others. It is endorsed by the Principal Secretary, MoE, and written by the RED. The Strategy sets the parameters for a policy and regulatory framework to support bioenergy development and highlights various bioenergy sources - including solid biomass fuels (including sisal briquettes and agricultural residues, including sisal, for cogeneration) and gaseous biofuels (including biogas).

The Energy Act of 2006 provided for the use bioenergy, specifically biogas, to generate electricity. It expanded the scope of electricity FiTs, which were first introduced in 2008 (Republic of Kenya, 2012b). The Energy Act (Republic of Kenya, 2019), which replaced the 2015 Energy Bill (Republic of Kenya, 2015), expanded the remit of the energy regulator through the creation of the EPRA. It also expanded the scope for bioenergy generators to sell their electricity to third parties, and to use the

national grid to 'wheel' renewable electricity from the point of generation to the point of consumption, upon payment of a wheeling charge.

Under the Energy Act (2019), all electricity generators above 200 kW must be registered with the EPRA. Those generating 200 kW to 1 MW for their own consumption do not require an EPRA licence, but they do require a licence for any sales to third parties and are required to charge an EPRA-approved tariff for those sales. Projects generating more than 1 MW all require licences from the EPRA, whether for self-consumption or grid sale. The applicable FiT for electricity generated from AD is USD 0.10 per kWh (Ministry of Energy, 2012).

The FiT process is currently being reviewed for simplification by a national committee set up to operationalise third party electricity sales and wheeling on the national grid, as authorised in the Electricity Act (2019). The EPRA sits on this committee.

The handling of sisal processing residues is covered by both national and county laws and regulations under the Environmental Management and Co-ordination Act (EMCA), Chapter 387 (Republic of Kenya, 2012a), primarily enforced by NEMA. NEMA requires an Effluent Discharge Licence (EDL) for any facility generating effluents that could harm ground water, surface water or coastal waters, and effluent tests are required at least annually to ensure compliance. EMCA establishes legal and institutional mechanisms for the management of the environment under three sets of regulations, namely: (i) Environmental (Impact Assessment and Audit) Regulations (2003), (ii) Environmental Management and Co-Ordination (Water Quality) Regulations (2006), and (iii) Environment Management and Co-Ordination (Air Quality) Regulations (2006).

NEMA's Environmental and Social Impact Assessment (ESIA) Department has inspectorates in every county responsible for overseeing ESIA development and compliance.

NEMA's Strategic Plan 2019-2024 (NEMA, 2019) focuses on "Green Economy for Sustainable Development", which is intended to support the use of renewable energy, production of crops using organic fertilizers and pest control methods. NEMA's requirements for effluent management and its focus on the green economy could provide good incentives to sisal producers to utilise sisal processing residues for AD for electricity generation (Republic of Kenya, 2012a).

3.3.3 Finance

Kenya is East Africa's regional financial hub, and sisal estates and smallholder farmers can draw upon major financial institutions such as the Commercial Bank of Africa (Kenya's largest commercial bank), Kenya Commercial Bank, the Cooperative Bank of Kenya, the National Bank of Kenya and Diamond Trust Bank, among others, all of whom provide equity and debt finance in the agricultural and industrial sectors. International banks active in the agricultural sector include Stanbic, Barclays, Standard Chartered and Bank of Baroda, among others. The Commercial Bank of Africa has been the most aggressive local financer of renewable energy projects, followed by the Kenya Commercial Bank and the Cooperative Bank of Kenya.

Companies' own finance and, in the case of imported equipment and machinery, export supplier finance/credit/guarantees/insurance, is often available for top-of-the-line equipment from such agencies as EH Group, Germany, COFACE, France,

Denmark's Export Credit Agency, DFC, the US Development Finance Corporation (ex-OPIC), the Export-Import Bank of the United States and SACE (Gruppo CDC), Italy's export credit agency, among a number of others when equipment is sourced from manufacturers in these countries.

3.3.4 Summary

Kenya's institutional and regulatory environment is supportive of the sisal sector, as an important source of rural employment and export revenue. A suitable regulatory framework is in place to incentivise sales of electricity from AD based on sisal waste, and controls on disposal of sisal pulp and liquid effluent provide an additional impetus to valorise those wastes. In the mid-to-late-2000s, there was considerable interest in using AD to generate electricity from agri-processing residues, including sisal wastes. 15 years after KPL's flagship investment, however, interviews with five of Kenya's sisal estate owners suggest that interest has waned signifcantly, mainly because the applicable FiT of USD 0.10 per kWh is economically unviable.

Moreover, Kenya Power, as the national utility, lacks the incentives to invest in upgrading its distribution infrastructure to handle new electricity generated from rural generators to feed into the grid. Six of the large estates are located in areas of low population density with relatively weak power grids, which would require the grid to be strengthened for embedded generation (e.g. from sisal AD electriciy generators). Kenya Power is reluctant to connect any embedded generation that cannot be despatched by themselves, particularly small-scale (sub-5 MW) embedded and intermittent generation.

4 OVERVIEW OF BIOENERGY CASE

4.1 PROJECT SUMMARY

Kilifi Plantations Ltd (KPL) is a 1,300 ha mixed sisal and cattle farm located just south of Kilifi on the Kenyan coast. KPL's sisal processing operation generates significant quantities of waste pulp from the decortication process. The farm also keeps a herd of heifers under shelter overnight, where their manure can be collected. The combination of decorticator waste and cattle manure generates sufficient waste to run an AD plant for waste management and power production.

In 2007, KPL set up a joint venture called Biogas Power Holdings (East Africa) Ltd (BPH) with the German companies agriKomp GmbH and Schnell Zündstrahlmotoren AG & Co. They jointly developed an AD plant to convert sisal pulp and cattle manure to biogas, from which to generate power for sale to both KPL and the national grid. With the support of GTZ, an AD plant was installed and is still operational today.

The project information below comes mainly from the owner of KPL, and from site visits in March 2021 and April 2017 (under an earlier phase of BSEAA), except where separately referenced. A selection of photos is in Appendix 6, together with additional photos from Migotiyo Plantations near Nakuru.

4.2 TECHNICAL DETAILS

4.2.1 Plant design

The main elements of the feedstock supply system and the AD plant at KPL are illustrated in Figure 3.5.

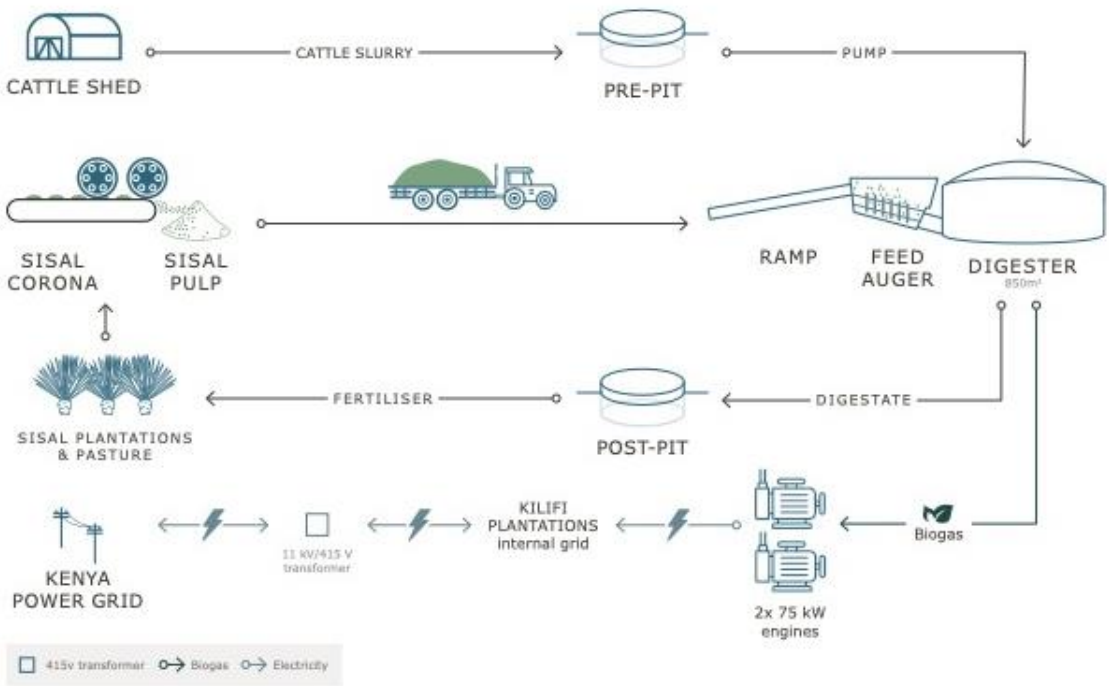

Figure 3.5. AD plant and feedstock supply system at Kilifi Plantations Ltd (Source: authors' compilation)

4.2.2 Plant details

AgriKomp installed a 850 m^3 continuous stirred tank reactor at KPL (750 m^3 for substrate and 100 m^3 for gas storage), plus a feeding system and agitator. Schnell supplied two second-hand modified Perkins 75 kW CHP engines (50 kW each plus 25 kW turbochargers). These dual fuel engines can also be run on diesel. The total reported cost was KES 37 million (~USD 600,000 in 2007), with 50% co-funding from the German Agency for International Cooperation (GIZ).

4.2.3 Feedstock

KPL produced around 400 t of brushed and baled sisal fibre in 2020, which would require 10,000 t of leaf (assuming 4% fibre content). Assuming that 90% of the leaf is available as pulp (Schwaninger, 2012, p. 8), the plant generates 9,000 t/yr of pulp, or an average of 24.7 t per day. The pulp from the decorticator is hauled by tractor-trailer to the AD unit, located 600 m away, where it is manually transferred to the digester via a loading ramp, hopper and feed auger.

The farm also has around 100 heifers stalled overnight, whose manure is used as an inoculant.[4] Schwaninger (2012) estimated that KPL's cattle would each produce an average of 58 kg of manure per day, but this was halved by Muntingh and Albertsson (2015) due to the animal's small size. With 100 heifers stalled at night and 75% of their manure collectable on a year-round basis (Schwaninger, 2012), the available manure is estimated at 794 t per year (2.18 t per day). The cattle shed is located close to the AD plant, and the manure is gravity-fed into a pre-pit and pumped from there into the digester, where it is blended with the sisal pulp.

KPL was also previously able to source mango pips and peels from a nearby juicing operation. Based on local experimentation and technical advice from the equipment supplier, the feedstock combination was fine-tuned to 14:3:2, sisal pulp : mango residues : cattle slurry. Mango residues are no longer available, as most processors now use these residues themselves as boiler fuel. With the removal of this waste stream, the current feedstock mix is approximately 6:4 sisal pulp : cattle slurry.

Table 3.2 calculates the biogas potential of these two feedstocks, based on a 25 day retention time and physical characteristics analysed by agriKomp (Muntingh & Albertsson, 2015; Schwaninger, 2012).

Table 3.2. Feedstock quantities, properties and biogas potential, KPL AD plant

Feedstock	Average input (t/day fresh matter)	Volatile solids (VS)		Biogas potential	
		% FM	t	Nm^3/t VS	Nm^3/day
Sisal pulp	24.7	12.27%	3.0	504.2	1,528
Cattle slurry	2.18	6.84%	0.15	358.8	53.5
					1,582

Based on these estimates, full feeding of the AD plant with all of the available residues could yield 1,582 normal cubic metres[5] (Nm^3) of biogas per day (higher during the 9-month sisal processing season and lower during the off-season). Assuming methane

[4] There were previously more than 300 dairy cattle at KPL, but there are far fewer since the sale of the dairy operation.
[5] A normal cubic metre is a standardised measure that would be the volume occupied by the gas under 'normal' conditions, i.e. 0°C and 1 atmosphere pressure (101.3 kPa).

content of 52% for sisal pulp biogas and 55% for cattle slurry biogas (Schwaninger, 2012), this suggests methane production potential of 824 Nm^3/day. With a net heating value for methane of 9.97 kWh_{th} per Nm^3, 30% generator efficiency and 90% availability, the available feedstocks could generate up to **67 MWh_e per month.**

In practice, the plant's owners have significantly reduced the rate of pulp feeding as they lack the commercial motivation to generate this much electricity (see 4.2.4), reducing average pulp input to only 4-5 t/day during the sisal processing season (thus averaging 3.4 t/day on a year-round basis). They only feed pulp from the first decorticator drum, which crushes the lower, thicker part of the leaf, and not from second drum. Some pulp is fed to the cattle (KPL, 2020).

At the reduced pulp feeding rate of 3.4 t/day, together with the full input of cattle manure, methane output should average 139 Nm^3/day (from 264 Nm^3/day of biogas). Even at this reduced feeding rate, it should still be possible to generate at least **11 MWh_e per month**, under the stated assumptions. The cattle slurry contributes around 21% of total methane output and electricity supply.

The electricity demand of the KPL operation is around 20 MWh_e per month during the sisal processing season. The largest single consumer is the 100 kW Stork S10-20 decorticator. The baler and other equipment require an additional 50 kW, for a total load of 150 kW when the facility is fully operational.

Despite the potential of the AD plant to generate at least 11 MWh/month for KPL, even at the reduced feed rate quoted, the gas generators are said to supply only around 5 MWh_e per month during the processing season, which is **3.75 MWh_e** on a year-round average basis. The significant electricity shortfall is procured from the grid. Feedstock input used to be higher, and monthly power production from the AD plant averaged 14 MWh_e over the first ten years of operation (from 2007 to 2017) (LTS International et al., 2016). So it is evident that both the feed rate and the power output of the plant are in long-term decline.

The power from the AD plant is sold to KPL and the digestate is given free as fertilizer. Heat is captured from engine cooling to keep the digester at 32-40°C. There are no other on-site heat requirements. KPL used to run a dairy under the Kilifi Gold brand and there had been a plan to replace a wood-fired boiler used for milk pasteurisation with a biogas-fired boiler. But the dairy has since closed, so process heat is no longer required.

4.2.4 Operation and maintenance

BPH's operation was a state-of-the art AD plant at the time of installation in 2007, with a high degree of automation (for example in the mechanical mixing and heating of the digestate, and in the operation of the engines, which could be remotely monitored from Germany). At its peak, KPL had reduced its electricity costs by 60% and BPH intended to refine the feedstock preparation by pre-processing the mango residues to achieve higher gas yields and potentially move to 24 hour operation (LTS International et al., 2016). The developer had reached an advanced stage of negotiation for an upgraded system with a 250 kW dual-fuel engine, to be co-financed by UNIDO. The Kilifi project was seen as a successful enterprise that generated sufficient revenue from electricity sales to return a small profit. KPL also benefitted

from the avoided disposal costs of sisal waste and the value of the digestate for the farm.

The AD plant still appears to be in reasonable working condition, even after 13 years of service. But the engines are clearly operating at very low capacity. While there has been some reduction in feedstock availability due to the termination of mango residue supply and a reduction in the availability of cattle manure since the closure of the dairy, there is still sufficient feedstock to produce close to 18 times more electricity than the plant is actually providing.[6] Although the digester and engines are now quite old, and components may not be operating optimally, BPH has two trained technicians who are capable of managing the plant well, and could increase the output of gas and power if it was commercially rational to do so. As the plant owner reported to the study team, "the problem is not the technicals". The challenges at Kilifi instead relate to a combination of policy and engineering, which mean that there is no motivation to run the system at its full potential.

On the policy side, small-scale power producers <200 kW do not qualify for PPAs from Kenya Power, so there is no provision for selling surplus electricity to the grid. One engine is capable of meeting KPL's entire needs,[7] and the PPA size restriction makes it pointless to run the second engine. Even if a PPA could be secured, the FiT of 10 US¢/kWh is unattractive and probably loss-making.

On the engineering side, Kenya Power applies a surcharge to any customer with a power factor below 0.9. The induction motors in the gensets need to be connected and synchronised to the grid to start. Since the maximum allowable voltage fluctuation is about 50 V, the system registers a fluctuation any time one generator goes off, resulting in the imposition of the surcharge. BPH has resolved to operate only one generator at a time to address this.

These constraints are experienced at Kilifi but are relevant for the whole sector. They mean that BPH has no incentive to utilise all the available waste and to optimise the AD process for maximum gas production and electricity generation. With no opportunity to sell to Kenya Power and the risk of a significant power factor surcharge, BPH never runs both generators at the same time and caps output at 50 kW.

The German shareholders have reportedly become "demoralised" by the experience, still partners on paper, but no longer involved in a practical sense. The expansion being considered in 2017, which would have increased electricity output above the PPA threshold and secured the ability to sell power to the grid (Muntingh & Albertsson, 2015) did not go ahead, presumably because the FiT was too low to make the investment worthwhile.

4.3 Economic assessment

Table 3.3 summarises the data used in the LCC model for KPL, as the Bioenergy Case, comparing it with a Base Case sisal processing operation drawing all electricity from the grid. For economic modelling purposes, BPH and KPL are considered as a single

[6] Potential monthly output of 67 MWh vs. an actual average of 3.75 MWh.
[7] They could meet their own demand for 20 MWh_e per month by running one of the 75 kW generators for 10.2 hours per day, for 26 days per month.

unit, despite them being separate legal entities with internal transfers of feedstock from KPL to BPH, in return for power sales and (free) fertilizer.

Table 3.3: Key project data for economic modelling of AD in sisal processing

Category	Parameter	Value
General parameters	Discount rate	10%
	General growth rate	8%
	Electricity retail price	KES 22/kWh (Kenya Power Commercial 1 tariff)
	Currency exchange rate	102.33 KES/USD
Base Case	Electricity consumption	187.5 MWh/yr (9 mths @ 20 MWh/mth; 3 mths off-season @ 2.5 MWh/mth)
	Diesel genset utilisation rate	10%
	Diesel cost	USD 0.95/litre
Bioenergy Case	CAPEX	USD 430,000 for AD plant (one engine only)[8]
	Biomass	2,037 t/yr (1,241 t sisal pulp + 796 t cattle manure)
	Biogas LHV	0.021 GJ/Nm^3
	Biogas methane content	53%
	Biogas consumption	28,302 Nm^3/yr
	Electricity self-production (with biogas)	45 MWh/yr (5 MWh/mth during 9 month sisal processing season)
	Feed-in tariff	USD 100/MWh$_e$

Figure 3.6 compares the $LCOE_{electricity}$ using 90% grid power plus 10% diesel gensets (Base Case) with the $LCOE_{electricity}$ using a combination of grid power and electricity from the AD plant (Bioenergy Case). The analysis indicates a cost increase from USD 473 to USD 726 per MWh. Figure 3.7 shows the same comparison with 50% of the CAPEX being grant-funded (in this case by GIZ). Even with this significant external support, the Bioenergy Case still shows a higher LCOE (USD 540/MWh) than the Base Case.

[8] Total CAPEX was USD 600,000, reduced to USD 430,000 for modelling purposes as only one of the engines is run at a time.

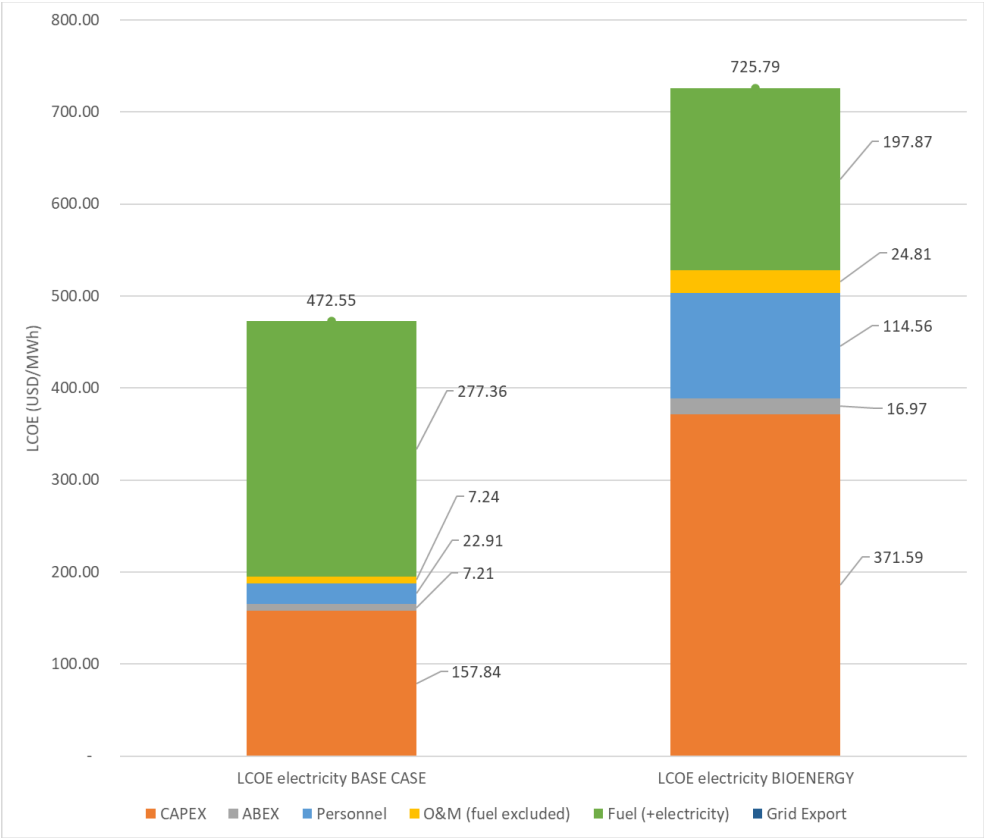

Figure 3.6: LCOE comparison of Base Case vs. Bioenergy Case

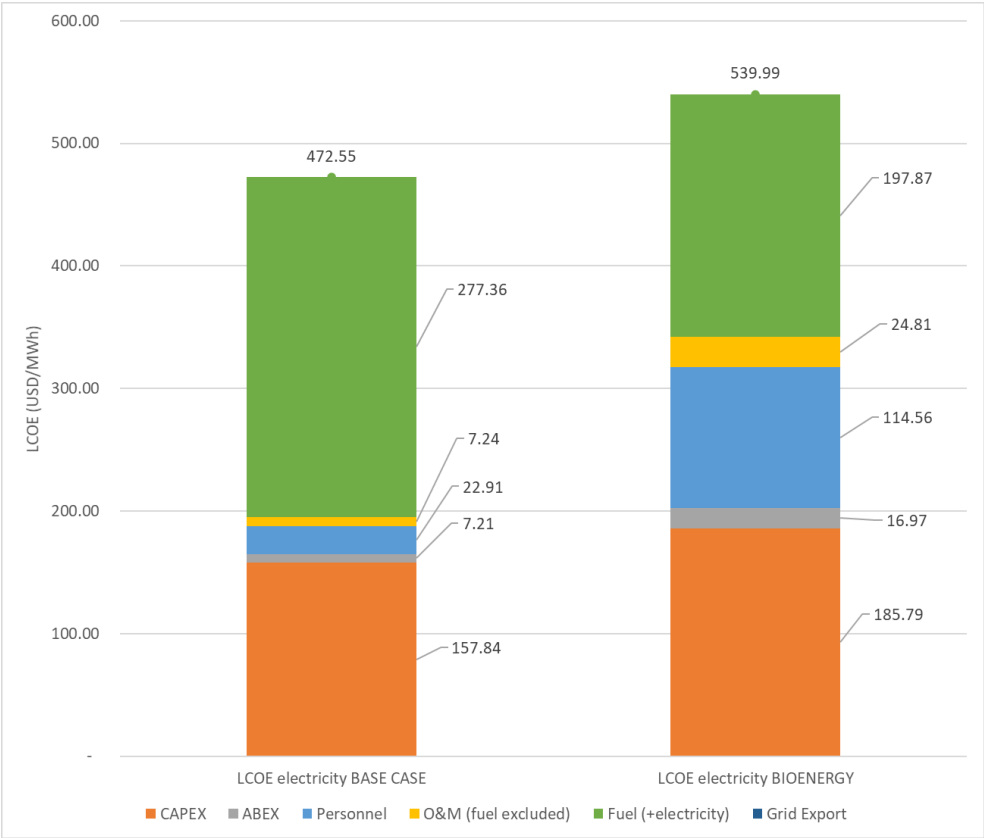

Figure 3.7: LCOE comparison of Base Case vs. Bioenergy Case with 50% CAPEX subsidy

4.4 Commercial success factors

Figure 3.8 provides details of the ownership of the different stages of the supply chain for the Bioenergy Case at KPL.

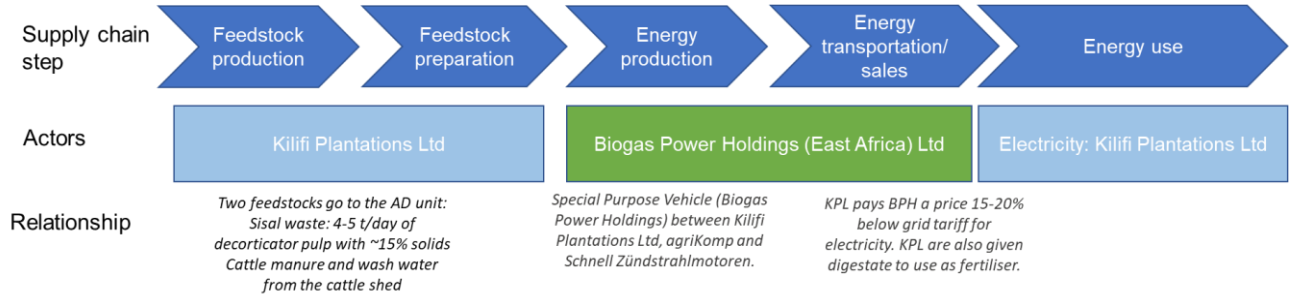

Figure 3.8. Overview of the supply chain for the KPL AD plant

The AD plant at Kilifi has struggled to achieve commercial viability. The preceding economic analysis indicates that BPH is not achieving a cost reduction in electricity under the current operating parameters. The unattractive FiT, the technical challenges associated with the interface with Kenya Power with respect to the application of power factor surcharges have disincentivised the project owners from increasing the feedstock rate, managing the plant optimally and producing more electricity than the minimal 3-4 MWh per month that is currently generated, by running one of the generators at low capacity for 3-4 hours per day.

Had these regulatory and technical problems not existed, there is every chance that the project could have been a commercial success. There are at least three supportive elements to the business model:

- **Large onsite electricity demand:** KPL's corona machine requires around 100 kW of electricity, and the sisal baler and other equipment a further 50 kW, between them accounting for nearly 90% of the operation's electricity demands. This high internal demand from two pieces of co-located machinery provides an ideal anchor load for the engines, at any time when sisal is being processed.
- **Waste disposal service:** KPL produces an estimated 9,000 t of sisal pulp every year, plus additional wash water from cleaning the fibres before drying. AD provides a solution to both dispose of this waste and to valorise it, in an environmentally beneficial manner.
- **Ownership model:** BPH is a Special Purpose Vehicle (SPV) that was appropriately set up to operate the AD plant and sell power to KPL, leaving KPL to focus on its core business of running the sisal estate, and firewalling the two operations, operational and financially. BPH does not pay KPL for the feedstock.

Given a more conducive FiT and a technical solution to address the power factor issue, the foundations were in place for a potentially successful commercial venture.

5 POTENTIAL FOR WIDER ADOPTION

This section assesses the replicability potential of the Bioenergy Case in the sisal sector, considering the five research themes of biomass resources, technology, economic competitiveness, commercial viability and the institutional and regulatory framework.

5.1 BIOMASS RESOURCE ASSESSMENT

5.1.1 Biomass potential from sisal residues

Kenya produces 23,000-27,000 t of sisal fibre per year grown on about 27,700 ha of plantation (Fibre Crops Directorate, 2019). Every tonne of fibre generates about 24 t of pulp and 100 m^3 of processing wastewater (Terrapon-Pfaff et al., 2012). While some of these residues may be used as fertiliser and animal feed, they are generally disposed of as waste on land or into water courses (FAO, 2020; Terrapon-Pfaff et al., 2012). To account for any alternative use and losses during storage and handling and that 3-5% is grown and processed at small-scale, the assessment assumes that 90% of the residues are potentially available for biogas production. At national level, this results in about 540,000 t of pulp and 2.25 million t of wastewater per annum (Figure 5.1).

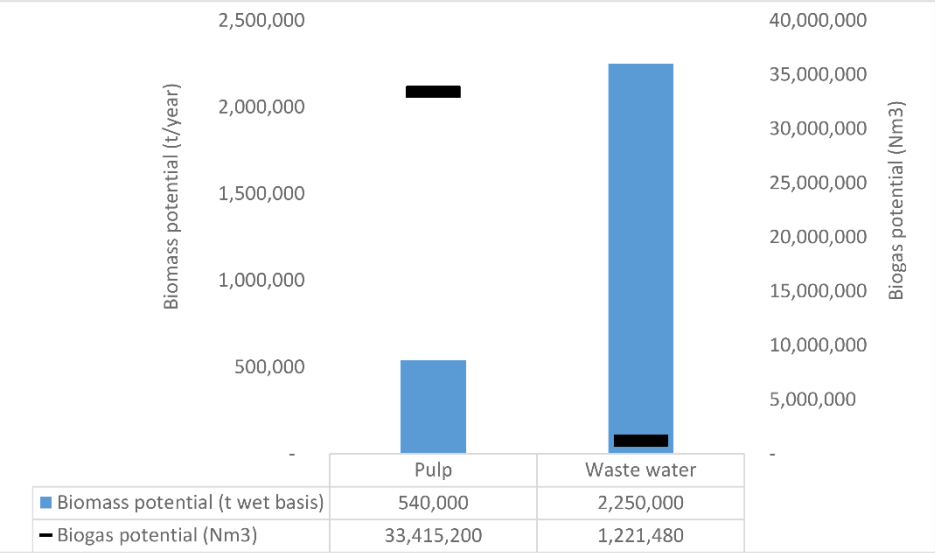

Figure 5.1. Biomass residues and biogas potential from sisal processing in Kenya

Sisal pulp has high volatile solids content of 12.3%, and high biogas potential of 62 Nm^3 biogas per tonne, giving total biogas potential for the industry of 33.4 million Nm^3 p.a. While wastewater represents a much larger quantity of potential feedstock, it has a high moisture content with only 1.2 g/l solids and a volatile solids content of 87% (FAO, 2020; Terrapon-Pfaff et al., 2012), and biogas potential of 0.55 Nm^3 biogas/tonne, which gives a total biogas potential of only 1.2 million Nm^3 p.a.. A total of almost 2.8 million t of combined feedstock (wet basis) are therefore available, with the potential to supply 34.6 million Nm^3 biogas per annum.

5.1.2 Mass-energy balance

Table 5.1 shows the mass-energy balance (MEB) parameters for using sisal pulp and cattle manure to produce biogas and generate electricity. The model input data are based on the specifications of the KPL plant.

Table 5.1. Mass-energy balance, bioenergy for electricity in sisal processing

Parameter	Units	Value
Biomass feedstock	%	61% sisal pulp : 39% cattle manure
Energy installed	kW_e	51.4 kW_e (one engine only)
Capacity factor	%	10
Annual operational hours	Hrs	876
Process	CHP to generate electricity	
CH_4 content of biogas	%	53%
Moisture content as received	%	Sisal pulp: 85 Cow manure: 91
Volatile matter content	%	Sisal pulp: 12.3% Cow manure: 6.8%
Electrical efficiency	%	30%
MEB model output		
Biomass flow	kg/s (wet basis)	0.2
	t/yr (wet basis)	631
MWh electricity/ t biomass	MWh/t (wet basis)	0.07
Biogas production	Nm^3/s	0.01
	Nm^3/yr	28,441
Energy		
Electricity	MW	0.052
	MWh/yr	45
Heat	MW	n/a
	MWh/yr	n/a
Loss	MW	0.12
	MWh/yr	105

KPL currently produces around 45 MWh of electricity per year from the AD plant, which contributes towards its total electricity demand. According to the MEB model, this should require 28,441 Nm^3 of biogas from 631 t of feedstock (taken as a mix of 61% sisal pulp and 39% cow slurry).

KPL in fact feeds the digester with an estimated 2,037 t/yr (796 t of manure and 1,241 t of sisal pulp), almost three times the quantity modelled, and with an installed generating capacity of 150 kW_e (two engines), it has the potential to produce at least 145.5 MWh per year (about 12 MWh per month), as discussed in 4.2.3. This would provide almost three times as much electricity as required for the sisal processing operations, offering additional opportunities for internal electricity use or sale. But the project owners are disincentivised from operating the AD plant and gas engines efficiently, or at anything close to their rated capacity, for the policy and technical reasons explained.

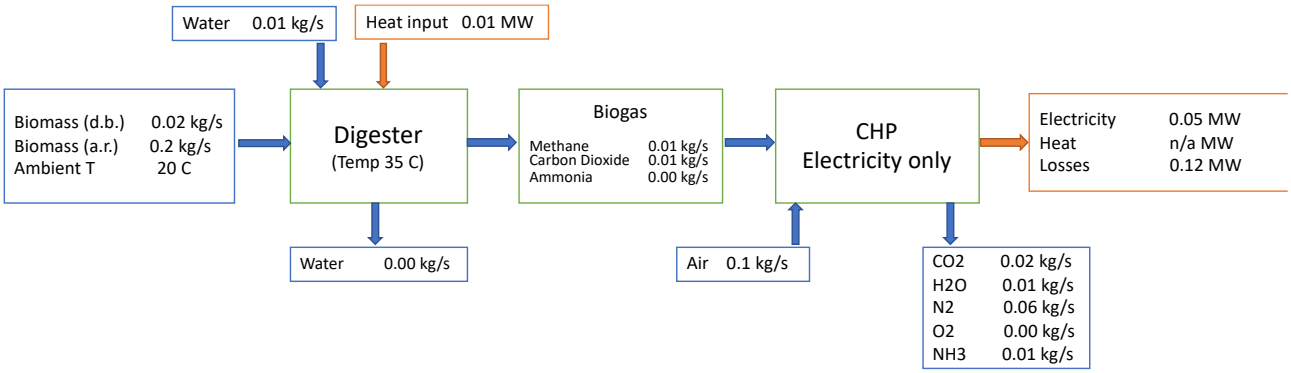

Figure 5.2.Mass-energy balance for electricity generation for sisal processing, based on KPL input specifications

5.2 Technology

Technology providers in Europe (and especially in Germany) have developed advanced AD systems that have been supplied to a number of projects in SSA. But the African market for this imported technology is still small and immature. Most European companies have supplied one project only, and none are thought to have installed their technology at more than two or three sites. Only Anaergia (owner of UTS Biogastechnik of Germany) is known to have full-time representation in SSA, with a regional office in Cape Town. But there is still little evidence that Anaergia, or indeed any other provider, has succeeded in gaining a dominant market share and achieving clear commercial leadership in SSA. This makes for a patchy and inconsistent technology supply landscape.

There are only two AD plants in SSA's sisal sector, with a UNIDO-funded facility at the Hale estate near Tanga, Tanzania, being the other. Hale has equipment from BioEnergy Berlin,[9] which went on to install an AD plant for wastewater treatment in Burkina Faso, but has not worked again with the sisal industry, or indeed in East Africa. AgriKomp, the equipment supplier to BPH in Kilifi, is not thought to have carried out any further installations in Africa. Other commercial-scale AD plants in Kenya have sourced equipment from AKUT and Snow Leopard, also from Germany, but these are also isolated examples that have not led to replication.

This lack of African experience among external technology providers, the high cost of European technology and the absence of local supply chains for equipment, servicing or spares, make it hard for other potential project developers in SSA to have confidence in the reliability and performance of particular international technology provider and their equipment, particularly in a sector with zero or very few other adopters, such as sisal processing.

High CAPEX and a patchy technology supply landscape are further deterrents to investment in a sector already deemed risky due to the inability to sell power to the grid, or to do so only at very low tariffs. The imported German equipment at BPH was relatively expensive, and the economic analysis (in 4.3 above) shows that even factoring in a 50% donor subsidy, it is still more expensive to produce electricity from the AD system as currently operated, than to buy power from the grid. While

[9] www.bebgmbh.de/flyer.pdf

economies of scale at higher operating levels would probably reverse this picture, a capital cost of USD 600,000 is still a significant entry barrier for a novel technology in an untested commercial setting such as the sisal sector. Reducing CAPEX with locally adapted technology could help boost the prospects for replication. The economic sensitivity analysis in the following section indicates that a cost reduction of 68% would have been required at KPL to deliver a long-term electricity supply cost comparable with that of power from the grid. This cost-reduction strategy is being pursued in Kenya by Olivado Biogas Ltd, and in South Africa by Cape Advanced Engineering, among others. It is a promising approach to enhancing the replication prospects for AD in SSA, not only in the sisal sector, but also for biomass residues more generally.

5.3 ECONOMIC VIABILITY

The economic viability of the Bioenergy Case is influenced by many factors, such as the amount of electricity produced, the CAPEX of the AD plant and the total electricity demand. In this section, the impact of these parameters on LCOE is investigated through sensitivity analyses. The linear regression lines in the charts are a simplified best-fit for the results from hundreds of simulated scenarios.

Figure 5.3 shows how the $LCOE_{electricity}$ varies with different levels of electrical output from the AD plant. In this analysis, KPL's electricity demand is assumed to be fixed, and as power generation is scaled-up, the model assumes that the surplus is sold to Kenya Power. As more biogas is produced and more power is generated, the LCOE gradually reduces. Using one biogas engine, a maximum monthly production of 22.5 MWh of electricity is possible,[10] which is sufficient to cover KPL's entire demand of around 20 MWh/month, and to generate a small surplus for potential sale to the grid. Beyond this output level, the second engine is brought on-stream, so a sharp rise is LCOE is recorded due to the additional CAPEX, but LCOE then reduces again as power output is increased. The modelling results show that the Bioenergy Case is not economically competitive for electricity production at any of the output levels, in comparison to the Base Case.

[10] Assumes 75 kW, 10 hours per day

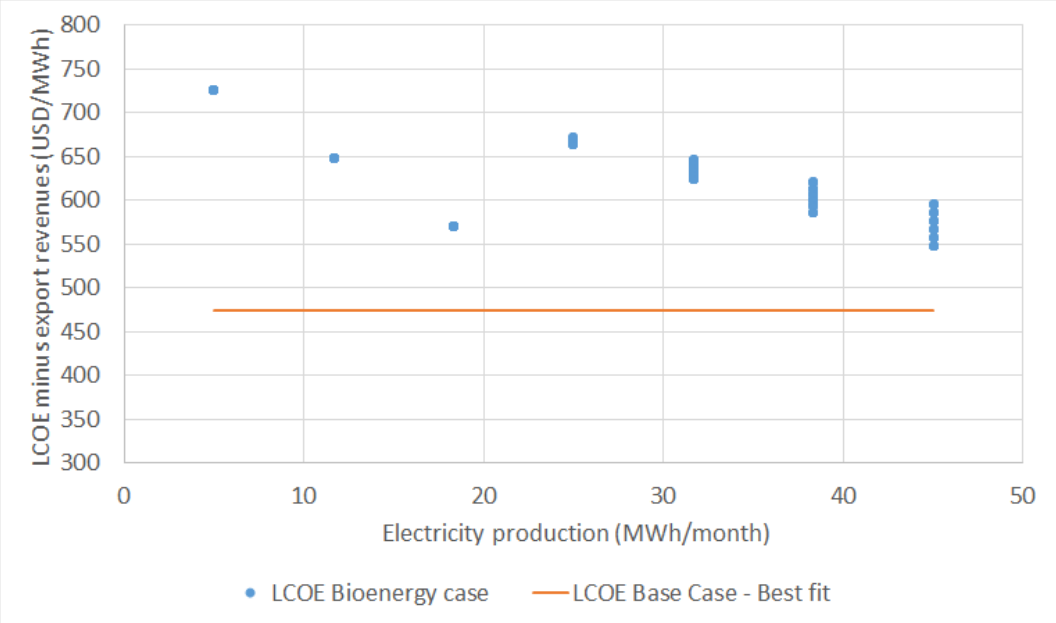

Figure 5.3: Sensitivity of LCOE to electricity production

Figure 5.4 illustrates the effect of different feed-in tariffs on LCOE, with electricity production of 45 MWh/month (using the two engines at full capacity). The results show that from a FiT of approximately USD 180/MWh (compared to the current FiT of USD 100/MWh), the Bioenergy Case becomes economically attractive. This is an important conclusion for the wider adoption potential of this bioenergy technology.

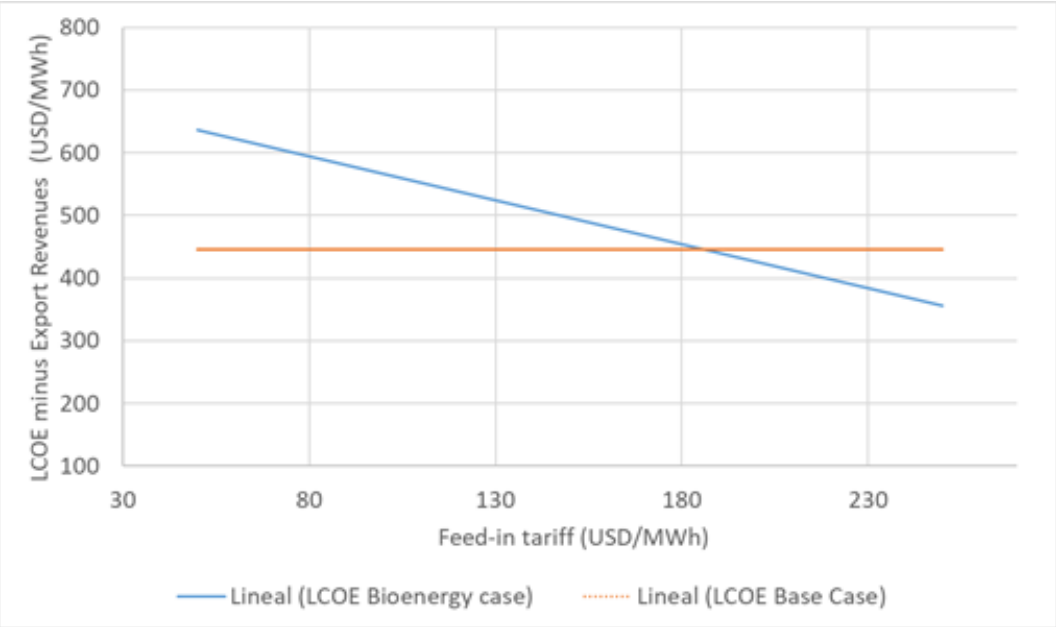

Figure 5.4: Sensitivity of LCOE to feed-in tariff.

Figure 5.5 investigates the influence of CAPEX on LCOE, starting from a baseline of USD 430,000 for the full AD plant with one engine. The results show that under current operational conditions, the Bioenergy Case would be economically viable vs the Base Case if investment costs were reduced by 68%, to around USD 138,000. This reduction could be achieved with external financial support or by sourcing cheaper equipment.

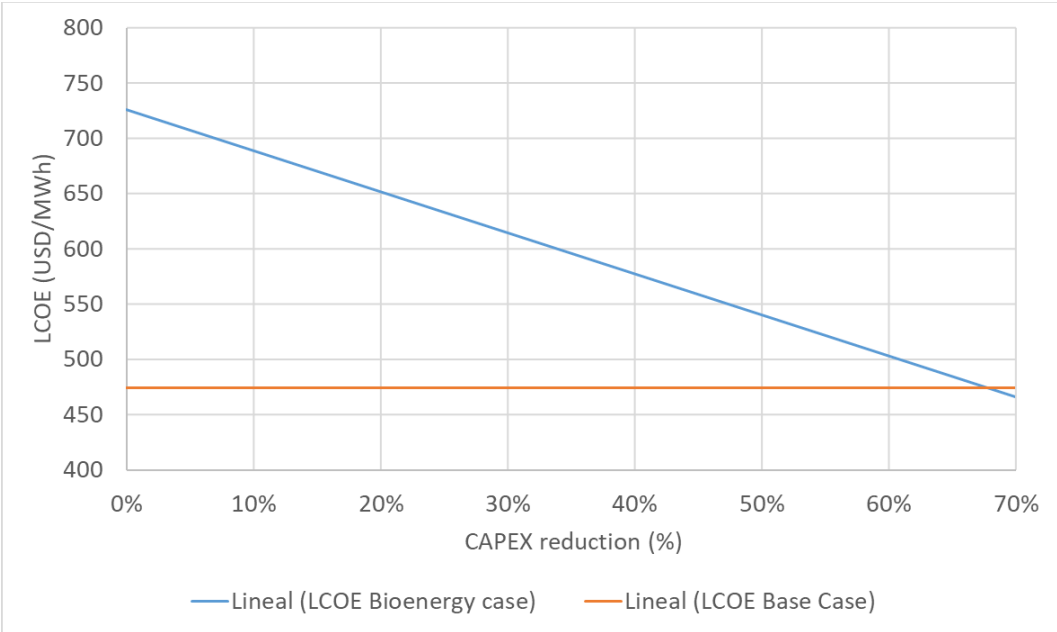

Figure 5.5: Sensitivity of LCOE to CAPEX reduction

Finally, Figure 5.6 studies the effect on LCOE the economic prospects of scaling-up the electricity demand. In contrast with Figure 5.3, this analysis explores an increase in KPL's electricity demand, without any sales to Kenya Power. Maximum practical output of the on-site engines is around 540 MWh/yr,[11] with any additional requirement purchased from the grid. The results show that from an electricity consumption of 600 MWh/year and upwards, the Bioenergy Case would be marginally more economically attractive.

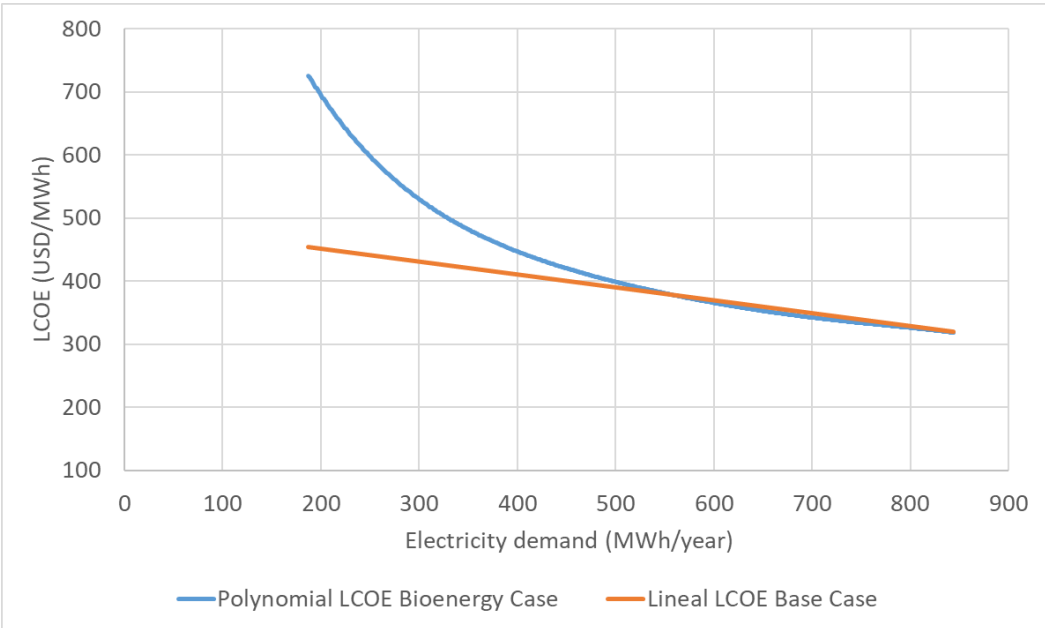

Figure 5.6: Sensitivity of LCOE to electricity demand

[11] Based on each 75 kW engine running at full capacity for 10 hours per day, every day of the year.

5.4 COMMERCIAL PROSPECTS FOR REPLICATION

5.4.1 Market potential

Kenya produces about 25,000t of sisal fibre on average each year (Fibre Crops Directorate, 2019)(FAO, 2021). The main drivers for AD-based sisal processing are electricity production and waste disposal. Heat has not traditionally been a requirement in the Kenyan sisal industry, although the use of steam is being considered at some facilities in Kenya for wilting the incoming leaves to facilitate decortication and to dry the wet fibre.

For every tonne of baled sisal fibre, 24 t of pulp and 100 m^3 of wastewater are produced (Terrapon-Pfaff et al., 2012). Given average production of 25,000 t by Kenya's sisal industry, this means a corresponding 600,000 t of pulp and 2.5 million m^3 of wastewater was generated. Assuming that 90% of this is recoverable, approximately 540,000 t of pulp and 2.25 million m^3 of wastewater are available for potential biogas generation. Further, assuming a wastewater electricity potential of 1.5 MWh_e per tonne of product and a sisal pulp electricity potential of 3 MWh_e per tonne of product (Terrapon-Pfaff et al., 2012), this suggests a total annual electricity generating potential for the industry of 112.5 GWh_e/year.

Unlike other demand sectors in this study, internal energy demand is not considered a barrier: each large sisal operation has an inherent electricity demand that can be easily met through AD. Consultations with estate owners indicate that specific electricity consumption for sisal fibre production is approximately 680 kWh_e per tonne of fibre, equating to an electricity demand of roughly 18 GWh_e per year. AD based on sisal decortication wastes could therefore comfortably meet the electricity requirements of the entire industry.

An estimated 95% of sisal fibre is produced by the 10 largest estates, which would be the maximum potential market for this technology in Kenya. Teita Estate and the two REA Vipingo estates represent more than half of total sisal production in Kenya. Some of the smaller of the ten large estates in Kenya might not have the critical scale necessary for a cost-effective investment in AD, so the actual potential market may be even more limited and must be determined on a case-by-case basis.

Teita Estate in Taita Taveta Country has plans to develop a 2 MW_e sisal waste-based AD system (P. Kyriazi, personal communication, 24 September 2020). In 2015, Migotiyo Plantations in Baringo County also considered installing AD, primarily for self-supply of power, through a GEF-UNIDO programme (GEF, 2015). Although they did not pursue this investment following a pre-feasibility study, there is still interest in exploring the opportunity if commercially viable (R.Gembali, personal communication, 12 March 2021).

There is therefore potential interest in AD in the sisal industry, but the preceding economic analysis suggests that this will only be economically competitive for a plant of similar size and processing system to that at KPL if there is a two thirds reduction in equipment cost and/or a rise in Kenya Power's FiT from USD 0.10 to USD 0.18 per kWh.

5.4.2 Market barriers

The key barriers and enablers that will determine the viability of AD in the Kenyan sisal sector are summarised in Table 5.2 below.

Table 5.2: Barriers and enablers to the use of biomass residues in the Kenyan sisal sector

	Barrier to business model	Enabling conditions
Electricity for self-consumption	**High variation in onsite electricity demand** KPL's main electricity consumers are the corona (100 kW) and baling machine (30 kW). The biogas generators are run only when there is a constant, full load from the corona. When the corona is switched off, so are the generators. This partly explains the high use of grid power (~15 MWh/mth). It is understood that there is no way to regulate the generators' supply to match the sisal plant's internal demand.	**Provision for net metering and correct power factor** There is a need for smart metering that credits KPL or any other potential future adopter whenever power is fed to the grid, with a correct power factor application, to incentivise the continuous running of the generators when the onsite load drops.
Electricity for grid export	**Lack of regulatory provision for small power producers to sell into the grid** Kenya's energy regulator (EPRA) does not permit independent power producers (IPPs) with less than 200 kW generating capacity to sell power to the grid.	**Regulatory reform** If the EPRA lowered the threshold for IPPs or made it easier for small generators to enter into wheeling agreements to sell electricity to third parties, the business case for AD at sisal estates and other potential power generators would be significantly strengthened.
	Non-viable feed-in tariff The FiT for power from biogas is only USD 0.10 /kWh, which is not high enough to justify investing in AD purely for export, nor large enough to justify the marginal cost of increasing AD capacity (as shown in Figure 5.4).	**Review feed-in tariffs for power form bioenergy** If the EPRA and Kenya Power made it easier for small generators to enter into wheeling agreements to sell electricity to third parties, or raised the FiT to at least USD 0.18/kWh, this could significantly strengthen the business case

	Barrier to business model	Enabling conditions
Waste management	**Sisal waste can be disposed of in other environmentally-compliant ways, but at a cost** KPL did not mention waste management as a driver for its AD investment. A large proportion of its liquid waste is not fed to the AD unit, but goes instead to an aerobic treatment pond, where from time to time it is used as fertilizer. Migotiyo Plantations and Teita Estate also dispose of liquid waste in ponds, with Teita having recently rehabilitated its treatment system to ensure NEMA compliance.	**Cost saving by using AD to achieve environmental compliance** Teita Estate highlighted the cost of waste management and treatment to comply with NEMA requirements as an important motivator for considering an investment in a 2 MW AD plant, which is currently under consideration. But high CAPEX will be a factor in determining this as a cheaper long-term waste management solution.

Sisal processing generates large quantities of waste suitable for biodigestion, which suggests significant technical potential for replication of the Kilifi AD venture at the other large sisal estates, based on avoided costs of disposal. However, the commercial case for such investments is limited due to the lack of interest in electricity procurement from sisal-based bioenergy on the part of Kenya Power, together with a lack of necessary regulatory support (particularly commercially-viable FiTs from the EPRA to make investment in bio-electricity from sisal and other bioenergy sources viable). Despite the inherently favourable internal demand for electricity from sisal processing operations, the commercial case for replication of the Kilifi venture is discouraging. Therefore, the main barriers preventing wider adoption do not lie with the producers, but rather the limitations of policy and the regulatory environment.

The opportunity cost associated with using AD as a wastewater treatment method, as opposed to aerobic treatment ponds, could improve the economic viability of replication. However, the high CAPEX requirement, and potentially longer-term return on investment, may deter investment in AD as an alternative wastewater treatment method. A successful business case will likely need to properly account for this opportunity cost to maximise wastewater collection and usage.

5.4.3 Finance

The AD plant at Kilifi was set up as an independent legal entity under the BPH registration, allowing risks to be separated and for the sisal processor to focus on its core activities. Accessing 50% donor support further reduced the financial risk for KPL.

Whilst it is understood that the idea to install an AD unit at Teita Estate is in its infancy, this is also envisaged to be owned and operated as a separate legal entity, with private funding. The AD plant is likely to be a joint venture (JV) between a South African project developer and the Teita Estate owners. The JV provisionally aims to sell power to Teita at KES 8-12 per kWh, compared with KES 17.5-19/kWh paid for grid power. Another sisal processor, Migotiyo Plantations, indicated that they could finance a potential AD project themselves, if the business case was convincing. This

therefore indicates that finance is not a major barrier for these large estates, if a convincing commercial case can be established.

5.5 Gender and inclusion

Given that the potential for bioenergy expansion lies within Kenya's large sisal estates, this analysis highlights the G&I issues around estate-grown sisal, rather than focusing on smallholder production. Women make up around 80% of sisal estate workers in Kenya, predominantly in low-skilled and low-paid positions, although one sisal estate reported women in high-level decision-making positions. Despite this, according to the field research, there seems to be limited awareness of the benefits of, and need for, engaging in G&I issues within estate-based sisal cultivation and processing. Barriers to accessing the formal justice system may further hinder women's access to the assets needed to benefit from being involved in sisal farming, whether estate-owned or smallholder. Few women seek to resolve land disputes through the courts due to the high costs and inaccessibility of legal aid organisations (Minoia, 2020). There have been around 400 family evictions over land disputes around the Lomolo, Kabaraka, Kilinga, Kipkureko and Alphega sisal estates. The families forced to leave included estate employees. This affected both women and men, and led to issues of lost income, diminished school attendance and worsening health due to homelessness or makeshift housing (ibid.).

Responses to field enquiries suggest a need for education around the meaning and benefits of social inclusion in the context of sisal farming, and why improving gender diversity could be a beneficial addition to sisal estate policies. There is little power for those who are facing barriers to inclusion due to the ability or access to legal rights, or resources for support, should disputes or mistreatment occur. Any organisation wishing to invest in bioenergy in the sisal sector should ideally consider capacity building for decision makers and staff as part of their support package, to ensure a common understanding on G&I and a framework that incorporates gender mainstreaming within company policy and promotes accountability.

Prior to such capacity building efforts, an externally conducted feasibility study is recommended to gain an understanding of the extent to which gender and social exclusion occurs, and the rights of employees and their families residing on sisal estate. With sisal estate ownership and land issues being a potentially sensitive area, it is all the more important to invest in clarifying G&I issues which may otherwise be omitted or deemed as not relevant and thus remain undocumented.

5.6 Institutional, market and regulatory framework

Despite considerable potential for generating electricity from sisal residues using AD, only KPL has so far made an investment in this technology. REA Vipingo's new CHP plant in Makueni County will generate heat and electricity using solid harvesting residues in more traditional combustion-based technology and will use most of the outputs for its own internal purposes.

The regulatory framework for sisal-derived electricity is governed by the EPRA, while any grid sales are on Kenya Power's technical, operational and power purchase terms. These terms are unattractive and have failed to stimulate significant investment. Sisal estates in Kenya's eastern counties of Kilifi, Kwale and Taita-Taveta also complain about poor Kenya Power infrastructure and reliability of supply, leading to extensive

use of their own diesel generators. This is not unique to sisal, as Kenya Power's network in much of rural Kenya affects most rural commercial agricultural producers.

In the late 2000s, there was significant optimism regarding the prospects for commercial AD in Kenya, with GIZ taking a particularly keen interest in the development of the sector, in part seeing the opportunity for German firms to supply technology and expertise. It was estimated that 20 MW_e of AD-based generating capacity could be installed at sisal plants alone, and a range of FiTs up to 18 US¢/kWh were proposed for AD installations (Fischer et al., 2010). This happens to be the breakeven point for economic parity modelled by this study for a mid-sized AD pant in the sisal sector. The Kenyan investment climate was evaluated as positive, and the local market was described as "an interesting entrance to the East-African biogas market for investors" (ibid.).

This optimism was based on the expected introduction of an attractive FiT system by the Government of Kenya, that did not materialise. The ability to feed surplus power to the grid is essential for the economics of an AD plant at a sisal processor, given that the power requirements of these plants are limited and variable. The lack of power sales to the grid has been a significant impediment to profitability at KPL.

The key recommendation is therefore for the Government of Kenya to double its FiT for biogas-derived electricity, with the EPRA making this a priority. The MoE and the EPRA should require Kenya Power to 1) prioritise electricity from biomass (including biogas); 2) put in place the mechanisms for doing so; and 3) strengthen the grid (particularly medium voltage), including transformers, inductors (for power factor correction) and basic distribution network wiring to improve reliability of supply. Imposing fines on Kenya Power for not meeting minimum standards in these areas would go a long way to ensuring that small-to-medium scale renewable electricity generators have good access to the grid, both for supplying electricity and for reliability of the supplies they take. Ironically, NEMA's enforcement of waste treatment and disposal regulations provides a greater incentive for AD than the renewable electricity legislation. The requirements for remediating sisal waste to meet NEMA's standards incur both fixed and recurring expenditures for sisal processors that could go a long way towards covering the investment in an AD plant. Much lower equipment costs and locally adapted technology would further boost the prospects for replication[12], notwithstanding the significant impediment presented by the low FiT.

5.7 Replication potential in other target countries

5.7.1 Introduction

This section explores the potential for wider adoption of the Bioenergy Case in the other BSEAA2 target countries. The intention is to summarise the prospects for replication of the model, based on the commercial environment in each of those countries and their respective sisal sectors, where applicable, but not to quantify either total energy demand in the sector, or the potential scale of the replication opportunity.

[12] On 30 June 2021, the Government of Kenya gazetted in the new Finance Bill that 'pre-fabricated biogas digesters' and the sale of 'biogas' are now exempt from VAT. This could stimulate further interest and possibly investment in AD from sisal residues in Kenya (Republic of Kenya, 2021).

5.7.2 Country sisal sector profiles

In addition to Kenya, sisal is grown in four other target BSEAA target countries, of which Tanzania presents the largest single opportunity for replicating the AD experiences of KPL in Kenya.

Tanzania: Tanzania vies with Kenya as the world's second or third largest sisal exporter, after Brazil. It produced about 24,000 t of sisal in 2018, down from over 70,000 t per year during the 1960s, of which over two-thirds is exported (Tanzania Invest, 2020). About 60% goes to China, 24% to Saudi Arabia and lesser quantities to India, Spain, Nigeria and Morocco (FAO, 2020). Exports are on a downward trend having decreased from about 25,000 t in 2017. As in Kenya, sisal in Tanzania is mostly grown on large estates of 500 to 12,500 ha, which account for about 75% of production (FAO, 2017; Tanzania Invest, 2020). The biggest growers are as follows:

- **REA Vipingo Group** owns three sisal estates via its subsidiary, Amboni Plantations, at Mwera, Sakura and Kigombe, located 50-70 km south of Tanga, which produce over 7,000 t/yr of sisal fibre (REA Vipingo, 2021).
- **Mohammed Enterprises Group** operates 11 sisal plantations covering over 40,000 ha in Morogoro, Tanga, Coast, Kilimanjaro and Lindi Regions. The group produces approximately 10,000 t/yr of sisal fibre, which is 35% of Tanzania's total output.
- **SFI Tanzania, a subsidiary of Form International**, has more than 3,000 ha of sisal with plans to expand to 6,000 ha. Most of the company's plantations are in Tanga Region and it sells to both local and international markets.
- **Katani Sisal** owns the Hale Estate near Tanga and installed an AD plant to generate power from processing residues with funding from the Common Fund for Commodities, via UNIDO. This project was profiled during BSEAA Phase 1 (2016-17). However, the plant is under-performing and has not been continuously operational for over four years.

These companies' plantations are capital-intensive, highly organised, mechanised and use high-yielding varieties. The industry engages over 100,000 people as smallholder farmers, workers in estates and contracted out growers (Tanzania Invest, op cit.).

Mozambique: Mozambique has a declining sisal industry that has gone from a peak of more than 30,000 t/yr of fibre in the 1960s to below 1,000 t/yr today. There is about 2,500 ha of land under sisal cultivation countrywide, mostly in Nampula Province, particularly in Monapo, Angoche, Mossuril, Ilha de Moçambique and Memba Districts. The sisal industry is characterized by small farms, with lower output and quality than other African sisal-producing countries (FAO, 2020).

South Africa and Ethiopia have never been large sisal producers. South Africa's production reached a maximum of some 8,000 t in the 1970s and has fallen since, while Ethiopia's production has been around 1,000 t/yr for the past four decades (FAO, 2017; WGC Services, 2020).

5.7.3 Potential for replication of Kenya's sisal sector AD experience

Kenya's experience with sisal-based AD is limited to Kilifi Plantations, which has not grown or been replicated elsewhere in the country. While it has operated longer than Hale Estate's AD facility in Tanzania, no further sisal-based bioenergy AD projects

have been developed in all of Africa, despite interest from the GEF, UNIDO and other development partners.

This includes continued interest by Common Fund for Commodities (CFC), via UNIDO both to expend the KPL facility and in supporting a new project at Migotiyo Plantations near Nakuru. Migotiyo is still interested in sisal AD-generated electricity, but with a reinforced Kenya Power grid passing close by, the cost does not currently justify the investment in an AD unit, again because of Kenya Power's reluctance to take on new rural electricity generation and the EPRA's low FiTs for power from biogas.

Teita Estate is considering an investment in a 2 MW AD system, partly as a means of treating liquid sisal residues, but is not thought to have taken concrete steps towards its realisation (P. Kyriazi, personal communication, 24 September 2020).

REA Vipingo (which has extensive holdings in both Kenya and Tanzania) has recently commissioned a 1.75 MW sisal residue CHP plant at its Dwa facility in Kibwezi, Makueni County (McDonnell, 2021). In contrast with KPL, this plant will burn solid harvesting residues from sisal poles and the boles of over-aged plants, using a well-understood combustion-based steam turbine system, rather than following KPL's lead in using moisture-rich decorticator residues and more novel AD technology. While not AD, it is the first use of sisal CHP combustion for own use, with a signed PPA with Kenya Power for sale of any excess electricity to the grid.

It is understood that the CHP plant will generate process heat for a new steam-based sisal decortication line and electricity for self-consumption and grid sale of any excess above own consumption. By producing heat and power primarily for internal use, this project has limited reliance on the sale of power to the grid, and the economic case is apparently stronger as a result.

While this operation does not use AD technology, it represents another potential bioenergy-based opportunity and pathway, particularly for the largest estates that produce significant quantities of dry residues from the pole offcuts and boles, which are extracted when the sisal plant has run its productive life cycle.

6 SUMMARY AND CONCLUSIONS FOR REPLICATION

Based on the analysis of the experiences at KPL and some other large sisal estates, a multi-criteria analysis (MCA) was carried out to summarise the degree to which each of the study's five thematic strands are conducive or detrimental to the successful adoption of AD in the sisal processing sector in Kenya. The results are presented in Figure 6.1, with a low score indicating an impeding factor and a high score indicating an enabling factor (see Appendix 5 for scoring details).

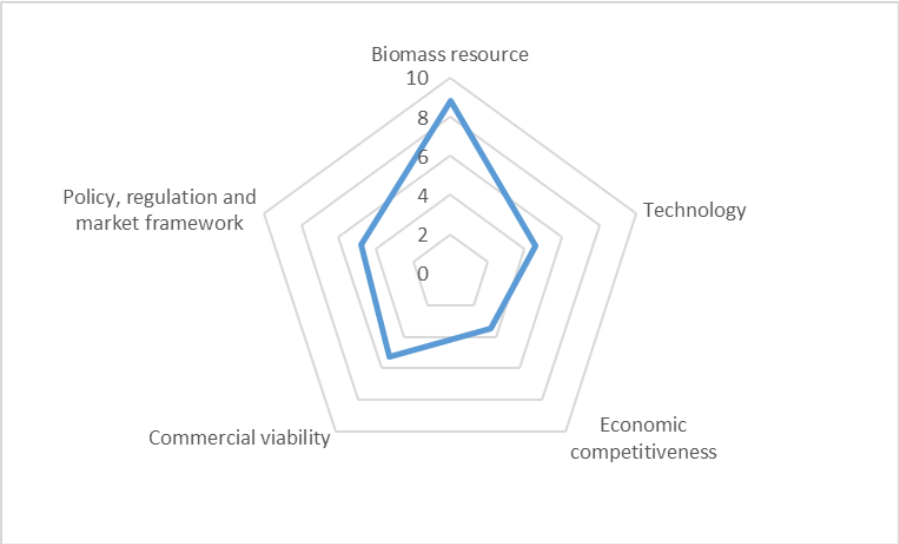

Figure 6.1: Impact of key factors on wider adoption of bioenergy case

Kenya is the world's third largest sisal producer, producing between over 26,000 t of sisal fibre per year, of which 97% comes from ten large estates and the balance from some 10,000 outgrowers and smallholders. In the mid-to-late-2000s, there was considerable interest in exploring sisal waste-based AD in Kenya to both generate electricity and to safely treat and dispose of decortication wastes. It was estimated that 20 MW_e of AD-based generating capacity could be installed at sisal plants alone, and a range of FiTs up to 18 US¢/kWh was proposed for AD installations.

However, only one sisal processor, Kilifi Plantations Ltd. (KPL), with support from GIZ (German development cooperation), has actually made such an investment. While this initial interest has since waned, because the expected introduction of an attractive FiT did not materialise, there is still a strong technical potential and interest from additional Kenyan sisal processors (such as Teita Estate) in AD-based energy generation.

The resource estimates for sisal in Kenya indicate that the current quantities of sisal processing wastes (in the form of pulp and wastewater) are more than sufficient to meet the electricity requirements of the sisal industry. Sisal residues are centrally located at processing plants and well-suited to biogas production. Given the lack of competing uses for these residues, which need to be safely treated and disposed of, their use as feedstock for AD also offers a waste management solution. There are also good opportunities to valorise the digestate from AD-based electricity production as a source of fertiliser for the estates and nearby farmers. Therefore, the availability of

sufficient feedstock is not seen as a barrier to wider replication of AD based on sisal residues, and in fact should be a motivating factor for its adoption.

Technology selection, sourcing and operation is considered a constraint to the wider adoption of AD in the sisal sector. Most providers of commercial-scale AD systems in SSA are based in Europe. KPL's AD investment was largely funded with German development funds, while a similar plant at Hale Sisal Estate near Tanga in Tanzania was largely funded by UNIDO, both using technology imported from Europe. These technology providers have typically supplied only one AD system, or a maximum of two or three, to African clients, indicating a small and immature market for this technology. The German technology partners in the KPL biogas project have become discouraged by the challenging commercial environment, following an optimistic start in the late 2000s, and are not thought to have been involved in any other AD installations in Africa. This lack of diverse, Africa-focused commercial experience, and the absence of supply chains in SSA for equipment, servicing or spares, means that other potential project developers lack confidence in the reliability and performance of sisal-based AD technology. High CAPEX is a further important deterrent to investment.

Based on the current operating parameters of the flagship project at KPL, the economic assessment indicates a higher cost of electricity from the AD plant, compared with grid electricity. Technical challenges linked to a power factor penalty by Kenya Power, and an unattractive FiT (USD 0.10 per kWh for biogas-based generation from 200 kW to 10 MW capacity) deters the project owners from utilising all the available waste to maximise electricity production. A sensitivity analysis demonstrates, however, that such an AD investment could be economically viable if the AD plant investment costs were reduced by 68% (to approximately USD 138,000) or if the FiT was increased to USD 0.18/kWh.

From a commercial perspective, a case can be made for replication of the Kilifi AD venture at the other large sisal estates, based on the inherently favourable internal energy demands, avoided costs of sisal waste disposal, the opportunity to meet the significant onsite electricity requirements linked to sisal processing and the potential to feed surplus power into the grid. Experiences from the project indicate, however, that this commercial case is currently weak primarily due to the lack of interest in electricity procurement from sisal-based bioenergy on the part of Kenya Power, and the lack of necessary support from the Kenyan regulator (EPRA) for commercially-viable FiTs to make investment in bio-electricity from sisal (and other biomass) financially viable. These factors potentially discouraged KPL from selling power to the grid. Furtermore, waste disposal is not seen as a key barrier, with many sisal estates deploying cheaper forms of waste treatment such as the aerobic ponds. Finance for such AD projects is not a major barrier, however, and the large sisal estates could potentially finance AD projects themselves, if the business case was convincing.

It is an important finding of the study that the key barrier to wider adoption of AD within the sisal industry in Kenya is the unattractive policy and regulatory framework for electricity generation and supply. Interest in sisal AD-electricity generation has waned significantly over the past decade, primarily due to a very low FiT for biogas-derived electricity. Moreover, Kenya Power lacks the incentives to invest in upgrading its distribution infrastructure to handle new electricity generated from small rural

generators[13] to feed into the grid, further discouraging investment into AD-based power generation.

Of the other four BSEAA2 target SSA countries that produce sisal (Tanzania, Mozambique, Ethiopia and South Africa), Tanzania presents the single largest opportunity for replicating the AD experiences of KPL in Kenya. The AD plant at Hale Estate, which is currently under-performing, suffers from a number of the same issues as KPL in Kenya, with inadequate policy and regulatory support, particularly for more attractive FiTs and long-term PPAs for sisal AD-generated electricity, similarly deterring interest and investment in this sector.

In sum, the opportunity for AD-based bioenergy generation in the sisal sector is currently discouraging, owing to the various, technological, economic, and policy and regulatory barriers that exist, although there is a potential for improving its commercial case. The key recommendation is for the Government of Kenya to increase its FiT for biogas-derived electricity to USD 0.18/kWh, with the EPRA making this a priority. The Ministry of Energy and the EPRA should require Kenya Power to 1) prioritise developing biogas electricity PPAs; 2) put in place the mechanisms for doing so; and 3) strengthen the grid to improve reliability of supply (particularly medium voltage lines in key sisal producing areas in eastern Kenya). NEMA's enforcement of waste treatment and disposal regulations, coupled with lower equipment costs and locally adapted technology, could further boost the prospects for the adoption of AD in the sisal industry. These recommendations are valid not only in Kenya, but also in Tanzania, which has a similarly large sisal industry and suffers from a number of the same constraints.

[13] Kenya Power, like TANESCO (Tanzania), Eskom (South Africa) and many other monopoly utilities, does not like to connect small-scale embedded generation because it is impossible to control their despatch of electricity, and Kenya Power wants to be able to control how much electricity is put onto the grid at any time.

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Appendix 2: People consulted

Organisation	Name	Position	Mode of contact
Electricity and Petroleum Regulatory Authority	Caroline Kimathi	Acting Director Electricity	Call
	Nickson Bukachi	Senior Renewable Energy Officer	Call
	Fenwicks Musonye		Call
Fibre Crops Directorate	Fanuel Lubanga	Manager of Market Research	Call
	Kabui Macharia	Field Manager, Cotton and Sisal Office	Call
Kilifi Plantations Ltd.	Chris Wilson	Managing Director	Call, Site visit
	Robert Anyoso	Plant superintendent	Call
	Erick Ogoti	Plant operator	Call
Migotiyo Plantations Ltd.	Peter Gachoka	Estate Manager	Site visit
	Venugopal Varanasi	Group Financial Controller	Site visit
	Elijah Masai	Production technician	Site visit
National Environment Management Authority	Zephania Ouma	Head of Compliance and Environment, Fibre Crops Division	Call
	Kennedy Odhiambo	Research and Planning Officer	Call
REA Vipingo	Neil Cuthbert	Managing Director	Call
Renewable Energy Directorate of the Ministry of Energy	JJ Gitonga	Deputy Director for Renewable Energy and Biogas	Call
	Eng. Kihara Mungai	Principal Renewable Energy Officer and FiT Specialist	Call
Teita Estate Ltd.	Philip Kyriazi	Managing Director	Call

Appendix 3: Assumptions in biomass resource assessment

The country-specific residual biomass potential was calculated based on amount of crop or primary product generated, the residue-to-product ratio, the recoverable fraction and the fraction of biomass available, considering other uses:

$$BMP=Cp*RPR*RF*OF$$

Where: BMP = available residual biomass in tonnes per year
Cp = crop production in tonnes per year
RPR = residue-to-product ratio in tonnes of residues per tonnes of product
RF = recoverable fraction per tonnes of product
OF = biomass fraction available after considering other uses per tonne of product

The theoretical bioenergy potential of this biomass resource was calculated considering the available residual biomass and its energy content.

$$BEP= BMP*(1-MC)*HHV$$

Where: BEP = bioenergy potential in GJ
BMP = available residual biomass in tonnes per year
MC = moisture content
HHV = higher heating value in GJ per tonne

Based on this approach, the following tables summarise resource available and biogas production potential of sisal residues in Kenya.

Biomass resource assessment

Crop	Feedstock	Sisal production (t/yr) [1]	Area of crop (ha) [2]	Total biomass (t)	Recoverable fraction	Biomass potential (t wet basis)	Biogas potential (Nm^3/t fresh matter) [3]	Biogas potential (Nm^3)	Solids content (wt%*) [3]	Volatile matter (wt%) [3]
Sisal	Pulp	25,000	27,638	600,000	0.9	540,000	56	23,868,000	15	85
	Wastewater			2,500,000	0.9	2,250,000	1	1,221,480	0.1	87

Crop	Feedstock	Production scale	Current use	Existing supply chain	Mobilisation
Sisal	Pulp, wastewater	Large scale (dominant) and small scale	Current uses are limited and often solids are disposed on land and liquids disposed to streams and surface water after basic aerobic and/or enzyme treatment. Residues can be used as animal feed, pharmaceutical ingredients, building material and fertiliser, and are suitable for AD.	yes	Generated as part of sisal processing

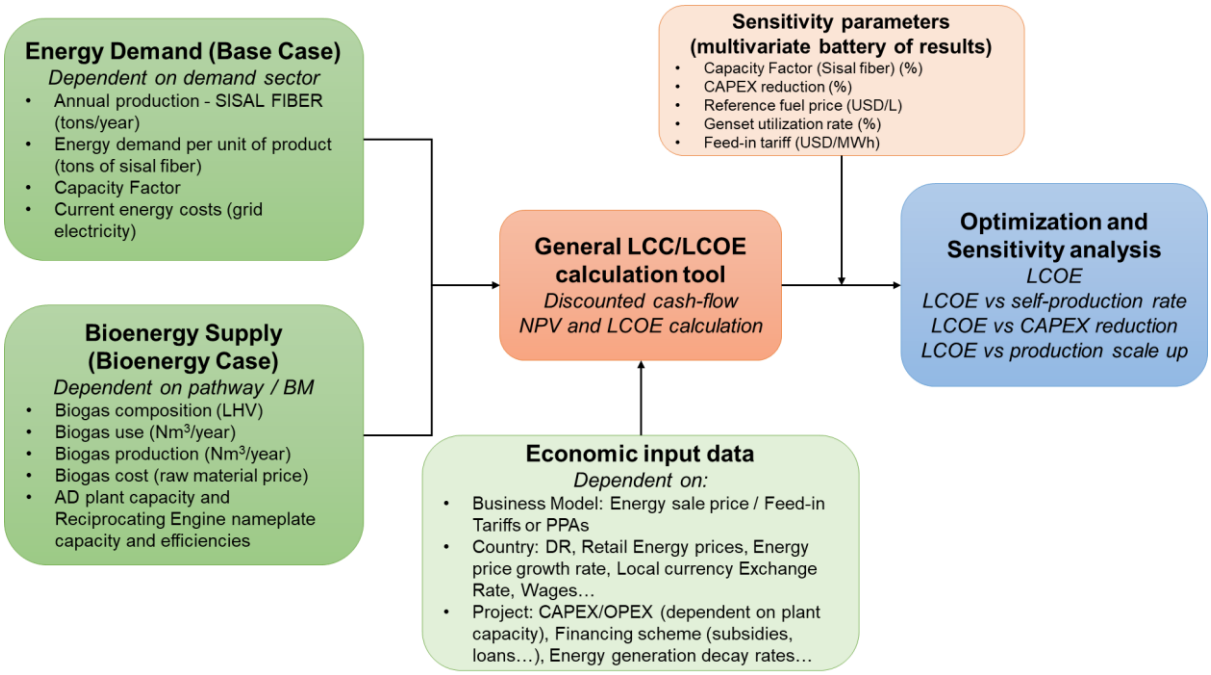
Residue-to-product ratios (RPR)

Crop	Residue type	RPR	Note
Sisal	Pulp	24	1 t of fibre results in 24 t of pulp [3]
	Wastewater	100	1 t of fibre results in 100 m^3 of wastewater in wet processing [3]

[1] (Fibre Crops Directorate, 2019) [2](FAO, 2021) ; [3] (Terrapon-Pfaff et al., 2012) *weight percentage

Appendix 4: Life-Cycle Cost toolkit functions

A flow diagram of AIGUASOL's Life-Cycle Cost (LCC) modelling toolkit functions is provided below:



The main economic indicator considered is the Levelized Cost of Energy (LCOE), in USD/MWh:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+\mathrm{DR})^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+\mathrm{DR})^t}(1+\mathrm{IR})^t}$$

Where: C_t = costs incurred in year t
DR = discount rate
E_t = energy consumed in year t
IR = annual inflation rate

Appendix 5: Multi-Criteria Analysis input data

Criteria	Score	Scoring criteria (Min=1)	Scoring criteria (Max=10)
Biomass			
Availability	7	low	high
Seasonality	9	short	long
Aggregation	10	scattered	centralised
Proximity	10	far	close
Technical feasibility	8	low	high
Average	**9**		
Technology			
Technology track record in same sector	5	low	high
Availability of a turnkey technology solution	4	limited	well established
Ease of operation and maintenance with in-house capacity	4	limited	well established
Supplier reputation, engagement and partnership	5	not engaged	engaged
Access to technical support & spares	5	low	high
Average	**5**		
Business model			
Energy self-consumption drivers	5	limited	significant
Grid and 3rd party export drivers	4	limited	significant
Waste disposal drivers (based on cost for disposal)	7	limited	significant
Market potential (replicate business model)	5	low	high
Average	**5**		
Policy, regulation and market			
Bioenergy policy	4	unsupportive	supportive
Bioenergy policy implementation	2	not implemented	implemented
Agriculture/Forestry policy	7	unsupportive	supportive
Agri/Foresty policy implementation	7	not implemented	implemented
Demand sector specific policy	4	unsupportive	supportive
Environmental policy	6	unsupportive	supportive
Environmental policy implementation	5	not implemented	implemented
Technology-specific fixed price (e.g. FIT)	3	unattractive	attractive
Demand sector specific governance practice	4	weak	strong
Biomass/processing specific governance practice	6	weak	strong
Average	**5**		
Cost			
LCOE electricity total	3	cost increase	cost reduction
LCOE electricity CAPEX	1	cost increase	cost reduction
LCOE electricity OPEX non-fuel	1	cost increase	cost reduction
LCOE electricity OPEX fuel or electricity	9	cost increase	cost reduction
Average	**4**		

Appendix 6: Photos of Kilifi Plantations AD plant, Kenya

Sisal plant

www.twenty2.net/wordpress/wp-content/uploads/2015/10/sisal_fields1.jpg

Sisal leaf feeding at corona machine
(Matthew Owen)

Sisal pulp
(Matthew Owen)

Sisal pulp loading into feed hopper
(Hannes Muntingh)

Feed hopper and auger
(Matthew Owen)

Cattle shed
(Bernard Osawa)

Biogas digester
(Matthew Owen)

Digestate pit
(Matthew Owen)

Gas engine
(Bernard Osawa)

1.75 MW sisal CHP plant at Dwa estate, Kibwezi (Andy McDonnell)