Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Demand Sector Report 2: Tea 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: Biomass boiler at Makomboki Tea Factory, Murang’a County, Kenya. Credit: Simon Thuo.

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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 second in the series, focuses on the bioenergy opportunities in the tea processing sector in Kenya.

Kenya is the world's largest exporter of black tea. Production is dominated by 650,000 smallholders through 70 factories under 54 farmer-owned companies. These companies are, in turn, shareholders in Kenya Tea Development Agency (KTDA) Holdings Ltd. Black tea processing requires significant quantities of thermal energy, which accounts for 90% of a typical factory's energy needs and up to 30% of costs. Heat is produced at all KTDA factories using fuelwood. With this energy source becoming more difficult and expensive to obtain in some areas, some factories have explored alternative fuels such as briquettes and agri-processing residues. The research explored the prospects for part-replacement of fuelwood with briquettes to provide heat for tea processing in Kenya.

Biomass supply was not found to be a barrier to wider adoption of this model. There is sufficient feedstock availability and briquette production capacity from KTDA's pre-qualified suppliers, plus others, to meet its goal of achieving 20% non-fuelwood biomass substitution at its factories. In terms of technology, suitable solid fuel boilers and ancillary equipment for withering and drying are available from reputable local and international suppliers, and there is a sufficient manufacturer support and operating expertise amongst factory staff and regional engineering teams to operate and maintain such systems, which can accommodate non-wood fuel blends.

The key bottleneck to the part-replacement of fuelwood is economic. Briquettes are around twice as expensive on an energy basis. While there may be boiler performance improvements attributable to the use of this drier and more standardised fuel, this cost differential has meant that only three KTDA factories have so far bought briquettes from KTDA's pre-qualified suppliers. Despite the cost barrier, there may be commercial motivations for a tea factory to consider using briquettes, including market sustainability stipulations, the need to ensure a diverse, durable and sustainable energy supply, and building supportive relationships with development partners. However, these benefits are currently insufficient to overcome the cost barrier. In order to make the relative costs of each fuel comparable, and to open up fairer competition, it would be appropriate to level the playing field by reducing costs incurred by tree plantation developers and briquette providers, such as taxes, movement permits and county cess payments. The Kenyan government's recent decision to remove VAT on briquettes is a positive step.

While the research currently suggests limited replication potential in Kenya and other shortlisted SSA countries, the potential exists for strengthening the business case for non-wood fuels through more equitable regulatory and fiscal treatment of biomass briquettes and sustainably grown fuelwood. This would support the diversification and strengthening of bioenergy supply chains on which tea factories depend, even while retaining a fuelwood-dominated supply system.

Contents

LIST OF ACRONYMS

ABEX	abandonment expenditure
BSEAA	Bioenergy for Sustainable Local Energy Services and Energy Access in Africa
CAPEX	capital expenditure
CTC	Cut, Tear, Curl (method of tea processing)
EATTA	East African Tea Trading Association
FAO	Food and Agriculture Organisation the United Nations
G&I	Gender and inclusion
IDH	The Sustainable Trade Initiative (original acronym in Dutch)
KEFRI	Kenya Forestry Research Institute
KES	Kenyan Shilling
KFS	Kenya Forest Service
KTDA	Kenya Tea Development Agency
KTDA MS	KTDA Management Services
KTGA	Kenya Tea Growers' Association
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LHV	lower heating value
MC	Moisture Content
MCA	Multi-criteria analysis
MEB	Mass Energy Balance
MoEF	Ministry of Environment and Forestry
MT	made tea
NEMA	National Environment Management Authority
OPEX	operational expenditure
RTA	Rwanda Tea Authority
SSA	Sub-Saharan Africa
TEA	Transforming Energy Access
USD	United States Dollar
ZAFFICO	Zambia Forest and Forest Industries Corporation

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 to catalyse 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 second in the series, focuses on the bioenergy opportunity in the tea processing sector 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**[1]		**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&veg processing residues		Kenya
6	Dairy	Cattle manure		S. Africa
7	Sisal processing	Sisal processing residues	AD electricity	Kenya

[1] Fuelwood: A solid biofuel originating from woody biomass, where the original composition of the wood is preserved (FAO, 2004).

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 tea sector are defined in Table 2.1.

Table 2.1: Base Case and Bioenergy Case for the tea sector

Base Case	Bioenergy Case
KTDA* factories using only fuelwood for generating heat for tea processing **** - Kenya Tea Development Agency***	KTDA factories substituting a portion of their fuelwood with alternative biomass resources for generating heat for tea processing **Flagship project: Makomboki tea factory, Murang'a, Kenya**

This report analyses the Bioenergy Case flagship project across the five 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 bioenergy as a source of thermal energy in Kenya's tea sector was based on web-accessed reports, journal articles, news reviews and interviews with government and private sector informants, supplemented by field visits and team members' own extensive experience in Kenya's tea, forestry and bioenergy sectors. It was particularly valuable for understanding Kenya's tea sector to track the establishment, growth and transformation of the Kenya Tea Development Agency (KTDA), from a government parastatal to a stock exchange-listed private company. Extensive consultations took place remotely and in person with staff of KTDA Management Services (KTDA MS), particularly its Managing Director and his team, and with the management of KTDA's Makomboki Tea Factory in Murang'a County. Field visits also took place to various suppliers of fuelwood and biomass briquettes.

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 relevant feedstocks in each demand sector. The assessment considered the spatial distribution of feedstock, according to FAO's Global Agro-Ecological Zones (FAO, 2021b) and the UN Economic Commission for Europe's framework for land use and agro-ecological zoning. Existing data on agriculture, forestry and agro/forest processing were used, adopting biomass feedstock categories from FAO (2004) and IEA & FAO (2017). Country and industry-specific resource potential was calculated based on the amount of crop or primary product generated, residue-to-product ratios, recoverable fractions, 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 heat in the tea sector in Kenya, based on technical considerations and practical experiences at the Bioenergy Case flagship project, Makomboki Tea Factory. Makomboki has been widely profiled as a pioneer and early adopter of alternative fuels within the KTDA network. Exploring the factory's experiences from a technical perspective required interaction with KTDA staff and fuel suppliers through both remote contact and site visits. The current technology and its supply chain landscape were characterised, and the opportunities and requirements for replication linked to technology were assessed.

2.5 Economic competitiveness analysis

The objective of this 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 the 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).[2] 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, LCOE was calculated for heat only. The model was also used to perform sensitivity analyses on LCOE considering a range of values for relevant input parameters.

2.6 Commercial viability assessment

The objective of the commercial viability 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 Makomboki was first analysed to identify the elements for commercial success linked, for example, to supply chain ownership, demand for heat and factors such as sustainability requirements and the development of international partnerships. Information about the operation was obtained from stakeholder interviews and literature review. This was followed by an analysis of the wider commercial potential of alternative fuels in the tea sector, analysing barriers and enablers for supplying heat under various scenarios. Taken together with an assessment of market size and conditions, the barrier analysis gave an indication of wider market potential. Potential sources of finance and their relevance for such bioenergy projects were also 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 the study's five key 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 factors (non-weighted) 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 report's 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.

[2] 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 Tea Sector

3.1 Sector Landscape

Kenya is the world's largest exporter of black tea (*Camellia sinensis*), earning over USD 1.4 billion in foreign exchange from tea exports in 2018. Over 60% of Kenya's tea comes from 650,000 small-scale growers, whose tea is processed at 70 independent factories under 54 farmer-owned companies. These companies are, in turn, shareholders in the Kenya Tea Development Agency (KTDA) Holdings Ltd. (IFC, 2014). Private estates, including both large multinationals (e.g. Unilever, Finlays, Williamson) and smaller private concerns, are represented by the Kenya Tea Growers' Association (KTGA). This report focusses mainly on the smallholder tea sector under the 70 constituent factories of the KTDA.

Most tea from both KTDA and KTGA members is sold via the 'Mombasa Auction', the world's second largest tea auction, under the framework of the East African Tea Trade Association (EATTA).[3] KTDA factories can also choose to sell to other buyers, including larger private estates (Oirere, 2017). About 20% of KTDA tea is sold on a bilateral basis outside the auction. This is mostly speciality teas for fair trade, environmental and organic markets. KTDA smallholder teas fetch an average price 20-25% higher than estate teas from KTGA members.

3.2 Tea Processing Method

KTDA factories produce black tea using the cut, tear and curl (CTC) process. As illustrated in Figure 3-1, the overall process involves withering, CTC, fermentation and drying, before the tea is graded and packed.

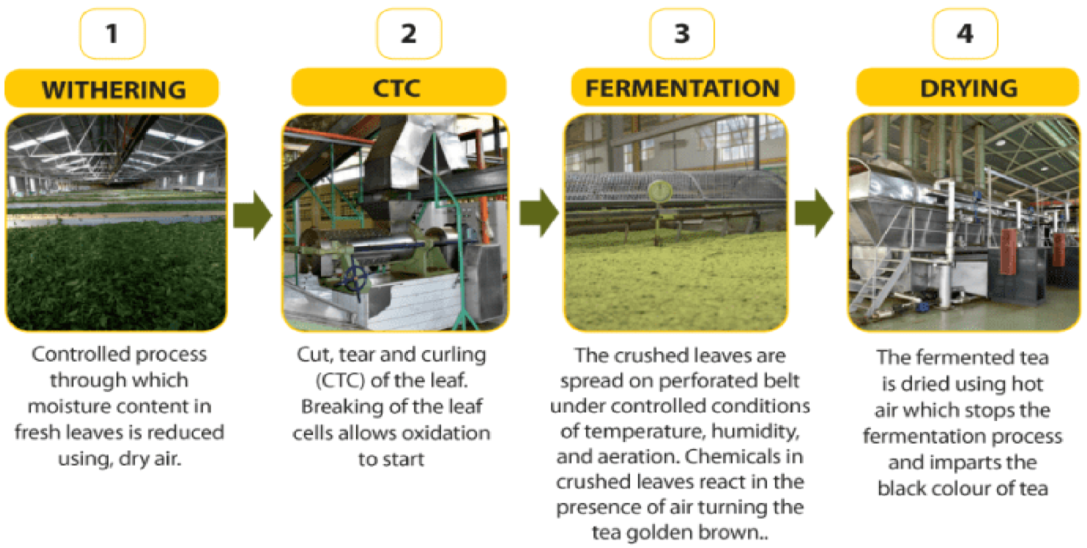


Figure 3-1. Black CTC manufacturing process (KTDA, 2020a)

Withering is the wilting of the fresh leaves to reduce moisture content (MC) from 75-83% to 65-66% (Kimari, 2012). The leaves are laid out in troughs and hot air is forced from below. The withered leaf is then reduced using the CTC method, in which

[3] EATTA represents companies and organisations from ten countries in east and southern Africa.

the leaves are passed through a series of cylindrical rollers with sharp teeth. For black (as opposed to green) tea, this is followed by fermentation, which browns the leaves and intensifies the flavour compounds. To halt the fermentation, the leaves are conveyed to the final drying stage. This is highly energy intensive as the MC is brought down to between 1 and 3%, using a strong flow of heated air through a fluidised bed dryer (ESMAP, 1987).

3.3 Bioenergy in the tea sector

The processing of black tea requires significant quantities of thermal energy. In fact, thermal energy accounts for 85% to 93% of the total energy used, with 90% being a representative average (GIZ, 2016; Inoti, 2016; Kimari, 2012). 60-70% of the thermal energy is used for drying and 30-40% for withering (GIZ et al., 2019). The heat is generated in central boilers to produce steam at 9-10 bar, 200^{o}C, which is conveyed to the withering and drying areas. For withering, the pressure is reduced to 4 bar, while drying requires higher pressure steam at 8 bar (ibid.).

In the absence of government regulations or incentives regarding energy for tea processing, fuel choice is driven by technical, financial and sustainability considerations at each factory. The majority of KTDA factories originally used fuel oil to power their boilers (ESMAP, 1987). These began to be replaced with wood-fired boilers under an African Development Bank project in the early 1980s, in response to rising oil prices and to promote a more sustainable image. KTDA had achieved full replacement with wood-fired boilers by 2012 (G. Oselu, personal communication, 6 June 2020). Fuelwood was initially purchased from local communities (CPDA, 2008) or from government forests, but KTDA factories had purchased 16,820 ha of their own land for fuelwood production and had planted 6,022 ha of their own trees by July 2019 (KTDA, 2020c), which provide supplementary fuel sources. Some KTDA factories also use supplementary bioenergy residues, including coffee husks, macadamia shells and others, when these are available.

The amount of energy used to produce a given weight of tea is a pointer to the efficiency with which a factory manages its machines and systems. Energy intensity in is quoted in terms of gigajoules (GJ) per tonne (t) of made tea (MT). KTDA's target is 20.8 GJ/t MT (GIZ et al., 2019), though energy intensity at a sample of KTDA factories has been recorded at between 28.8 and 31.0 GJ/t MT (Inoti, 2016; Kimari, 2012),[4] reflecting inefficiencies in some factories' operations.

Smallholder tea farmers in Kenya have seen their incomes fall by around 30% due to rising production costs and falling prices in global markets (Rees, 2019). Given that energy accounts for up to 30% of total costs, KTDA factories are incentivised to improve the efficiency of energy use prompting KTDA to embark on an energy rationalisation programme.

Although **electricity** accounts for no more than 15% of energy consumption at a typical factory, it represents 50-60% of energy costs (GIZ, 2016; GIZ et al., 2019). Reducing electricity demand and stabilising supply has therefore been a priority for

[4] Inoti (2016) collated fuelwood records from 9 factories over 5 years, to give an average of 34.3 GJ/t MT. But he assumed a lower heating value (LHV) for fuelwood of 14.4 GJ/t, whereas adopting a more realistic LHV for wetter wood (~13 GJ/t) implies a lower energy intensity of 31 GJ/t MT. Kimari (2012) reports 7.2 kWh (25.9 GJ)/kg MT for thermal use only, which implies an energy intensity of 28.8 GJ/t MT, on the assumption that 90% of energy use is thermal.

KTDA. KTDA factories have set up a power company (KTPC Ltd) to invest in hydro-electricity projects, with five currently operational and nine under construction with support from the IFC (KTDA, 2020b),[5] and have also commissioned energy audits, replaced inefficient fans, motors and lighting, and trained staff on energy efficiency. Such measures contributed to a drop in energy intensity across the KTDA network of 15% between 2013 and 2017 (ibid.). The Agency is constantly undertaking reviews to further improve efficiency, which translates to lower energy costs and more money in farmers' pockets.

There have also been efforts to improve the efficiency with which **thermal energy** is used, which are described in the 'Bioenergy Case' at Makomboki, profiled in section 4 below. With fuelwood becoming more difficult and expensive to obtain in some areas, KTDA has had to take innovative measures to secure sustainably sourced fuelwood. It has purchased almost 17,000 ha of land for fuel plantations and is looking to purchase a further 50,000 ha. Its factories have planted 15,500 ha of their own woodlots (KTDA Holdings, 2020), while its smallholder farmers are required to plant 1 ha of fuelwood trees per 4 ha of planted tea (KTDA Holdings, 2021).[6] Some factories have also been motivated to use alternative forms of biomass such as biomass briquettes or agri-processing residues (e.g. coffee husks, macadamia shells, etc.), contributing to a KTDA goal of achieving 20% non-wood bioenergy substitution.

3.4 Institutional, regulatory and finance framework

3.4.1 Institutional framework for the tea sector

A strong institutional framework has been key to the success of the Kenyan tea industry (Figure 3-2):

- **Public sector** actors, including government ministries, agencies, institutes and regulators, create an enabling environment by developing and implementing favourable policies, legislation and regulations, as well as providing research and trade promotion support for the tea sector;
- **Private sector** actors, including smallholders and estates, concentrate on tea growing, processing and exports, working with finance institutions, equipment suppliers and maintenance companies, and with tea trading, marketing and export companies; and,
- **Non-government** actors, including industry and growers' associations, and auctioning bodies, support producers in farming, processing and sales.

Sessional Paper No 2 of 1999 (Ministry of Agriculture, 1999) started the process of privatising KTDA. This set the stage for the privatisation of KTDA through the Companies Act, Cap 486, 2000, whereby the Kenya Tea Development Agency Ltd was established as a limited liability company. This was renamed the Kenya Tea Development Agency Holdings Ltd in 2009 and the KTDA Management Services (KTDA

[5] Factories have not found it viable to install combustion-based CHP systems, as it is more cost-effective to use the limited supplies of biomass for dedicated thermal use. CHP would require boiler replacement, as tea processing requires low pressure steam (8-12 bar), whereas CHP requires high pressure steam (35-50 bar) for backpressure or extraction turbines (US Dept. of Energy, 2016).
[6] KTDA MS has agreed this target with its shareholder factories, with financing available through the KTDA Foundation. See www.ktdafoundation.org

MS) subsidiary was formed to serve as the primary management support unit serving all 54 tea companies and the 70 KTDA tea factories.

Every tea factory in Kenya is licensed through the Ministry of Agriculture's Tea Directorate on all aspects of production, processing, grading and export, under the Tea Act, Chapter 343 (Republic of Kenya, 2012) and the Companies Act No. 17 (Republic of Kenya, 2015). Since 2014, the regulatory body for the tea sector has been the Tea Directorate of the Agriculture and Food Authority's (AFA), after the new Crops Act (Republic of Kenya, 2013b) disbanded the Kenya Tea Board.

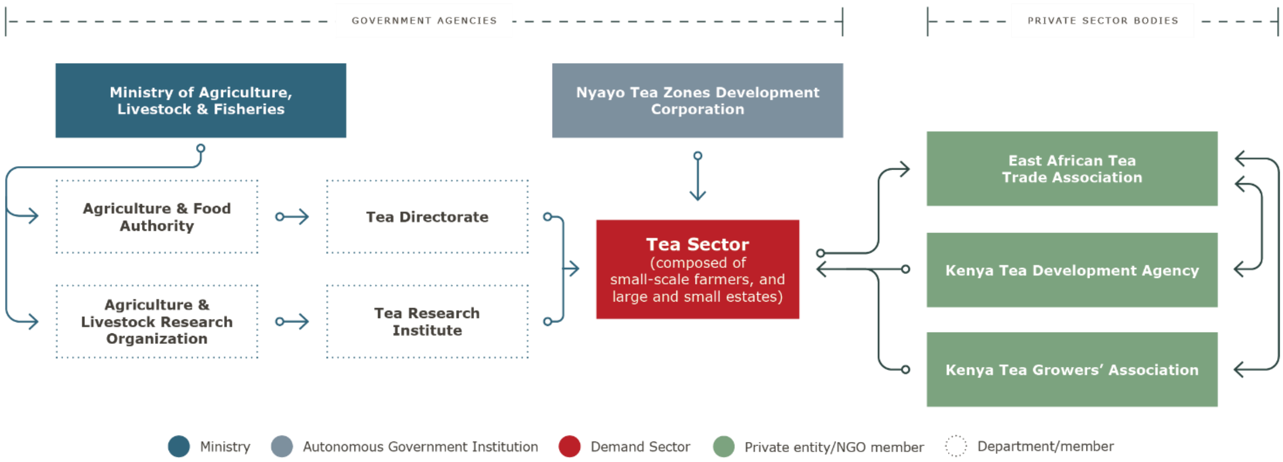


Figure 3-2. Institutional framework in Kenya's tea sector[7] (Source: authors' compilation)

While KTGA's 38 members represent private estates and their out-growers under local and international ownership, KTDA represents 650,000 small-scale producers and their 54 farmer-owned tea companies. KTDA has the following eight subsidiary companies serving its members and supporting the tea value chain:

1. KTDA Management Services provides management support to the factories,
2. Chai Trading Company manages factories' primary sales and marketing,
3. Majani Insurance Brokers provides insurance to factories and farmers,
4. Kenya Tea Packers purchases, packages and sells some tea from KTDA factories, mostly for the local market,
5. Greenland Fedha provides micro-finance to KTDA members,
6. KTDA Foundation is a benevolent association and also invests in and operates fuelwood plantations,
7. The Tea Machinery and Engineering Company provides machinery and technical support to the factories, and
8. KTDA Power Company develops and operates renewable electricity supplies for KTDA factories.

3.4.2 Regulatory framework for the tea sector

The regulatory framework for Kenya's tea sector is relatively light. The Agriculture Act (Republic of Kenya, 2013a) provided the legal framework for a stable agricultural

[7] The Nyayo Tea Zones Development Corporation (Republic of Kenya, 2002) was established as a state corporation, not only to grow tea, but also to protect Kenya's National Parks and Reserves by planting tea along their boundaries. This was intended to prevent intrusion by people and to keep wildlife inside, thus limiting damage to crops and property. The Corporation has over 2,000 ha of tea and four tea factories, and also takes tea to KTDA and KTGA factories for processing.

sector by regulating for good management and husbandry practices, but had no specific regulations pertaining to tea.

The Crops Act (Republic of Kenya, 2013b) covered tea, but was supplemented by the Crops (Tea Industry) Regulations (Ministry of Agriculture, 2020) and the Tea Act (Republic of Kenya, 2020). These aligned and simplified the regulations for the tea industry with the rest of the agricultural sector. The Tea Industry Regulations cover the production, marketing, trade and export in tea, as well as registration and licensing matters. Bringing the tea sector under a single set of regulations has reduced the regulatory burden, making it easier for the industry to comply and for the government to enforce.

Smallholder tea factories are limited liability companies under the Companies Act No. 17 (Republic of Kenya, 2015). This gives them leeway to set their own policies and strategies for tea growing, processing and marketing, and also for their sourcing and use of energy.

3.4.3 Institutional and regulatory framework for bioenergy in the tea sector

As fuelwood is the key thermal energy source in both the smallholder tea sector (primarily KTDA factories) and the estate tea sector (KTGA), forestry policy and regulation play a major role in how tea is produced and defines its impact on Kenya's forest landscape. The Kenya Forest Act (Government of Kenya, 2012) forms the basis for all forestry activities and organisations in Kenya while the Forest Act (ibid.) governs the relations between the Ministry of Environment and Forestry (MoEF) and industries with respect to fuelwood.

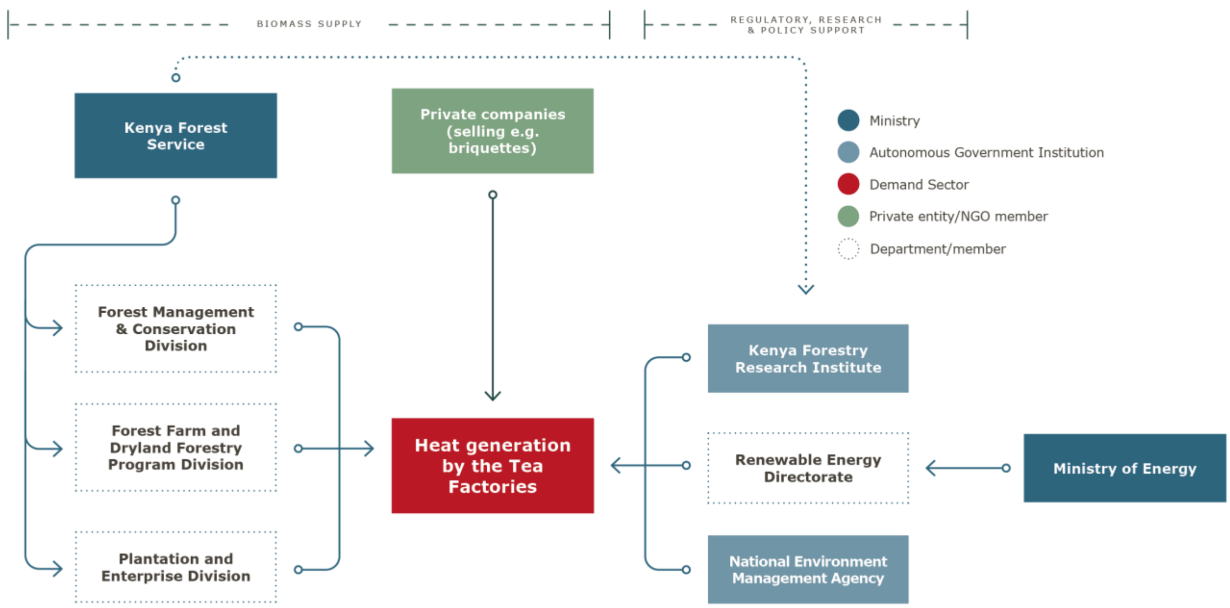


Figure 3-3. Institutional framework for biomass energy in Kenya's tea sector (Source: authors' compilation)

The MoEF is the apex body for all affairs concerning forestry in Kenya. Under MoEF is the (a) Kenya Forestry Research Institute (KEFRI), a parastatal organization that carries out research into forest products, including bioenergy, (b) the National Environment Management Authority (NEMA), a semi-autonomous agency that supervises, coordinates and implements environmental policies and regulations, including in tea growing and processing, and (c) the Kenya Forest Service (KFS), a parastatal founded in 2016 under the Forest Conservation and Management Act (Republic of Kenya, 2016) which oversees all of Kenya's forestry resources, and is the regulatory, standards and licensing agency for private forestry production. KFS manages 135,000 ha of state-owned plantations, from which many KTDA factories purchase fuelwood (Figure 3-3).

Since switching from fuel oil, KTDA factories source fuelwood from (i) mainly factory small fuelwood plantations and woodlots on KTDA-owned land (~35,500 ha), (ii) forest estates and woodlots owned by KTDA smallholders who sell the fuelwood to the tea factories they own and sell their tea to, (iii) other private farmers with their own plantations and woodlots, and (iv) commercial forestry companies and v) KFS commercial plantations. Some 18 KTDA factories currently or in the past few years have sourced additional forms of sustainable bioenergy (e.g. briquettes, nut shells or coffee husks), in accordance with KTDA's goal of achieving a 20% non-fuelwood blend for their tea producing factories.

Fuel choice at each factory is driven by straightforward availability, financial, sustainability and performance considerations. There are no regulatory, financial or other incentives for using bioenergy in tea processing. Although the government recently introduced a bill resulting in 14% VAT on certain imported components for solar PV, bioenergy and wind, this was amended from 30 June 2021 and briquetting machinery now attracts zero VAT (Republic of Kenya, 2021). This could stimulate more sales of biomass briquettes to KTDA factories. However, equipment for thermal use of bioenergy (e.g. boilers, electronic controls and motors) receives no import duty, tariff or VAT relief. The sale of fuelwood from commercial plantations is also subject to 14% VAT, whereas fuelwood bought from individual farmers avoids this charge. The harvesting and transport of fuelwood is subject to additional fees and permitting requirements, payable to both KFS and county governments.

3.4.4 Finance

The KTDA Foundation finances fuelwood plantations and land purchase for tea factories and offers other financial services to KTDA factories. Kenya is East Africa's regional financial hub, and tea farmers and factories 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 agriculture, forestry and industrial sectors. International banks active in the agricultural sector include Stanbic Bank, Barclays, Standard Chartered and Bank of Baroda, among others. In terms of planting trees for tea factories, the KTDA Foundation, which has a finance arm, provides KTDA MS and individual factories with finance to buy land and establish woodlots, for supply of fuelwood to KTDA factories.

Entrepreneurs considering establishing production facilities for the manufacture of non-fuelwood biomass, such as briquettes, need to secure their own finance. For any 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 (EKF); UK Export Finance; the US Development Finance Corporation (ex-OPIC); the US Export-Import Bank; and SACE (Gruppo CDC), Italy's export credit agency, among a number of others, when equipment is sourced from these countries.

4 Overview of Bioenergy Case

4.1 Project summary

Makomboki Tea Factory, one of 70 in the KTDA network, is located in Murang'a County, approx. 90 km north of Nairobi, at an altitude of 2,160 m on the eastern slopes of the Aberdares Mountain Range (see map in Figure 4-1). The factory opened in 1981 and processes tea from 5,096 growers, who between them cultivate 1,742 ha of tea. With a conducive climate and average annual rainfall of 1,400–1,500 mm, conditions are favourable for tea growing all year round. The factory's annual output of made tea averaged 6,203 t between 2018 and 2020.

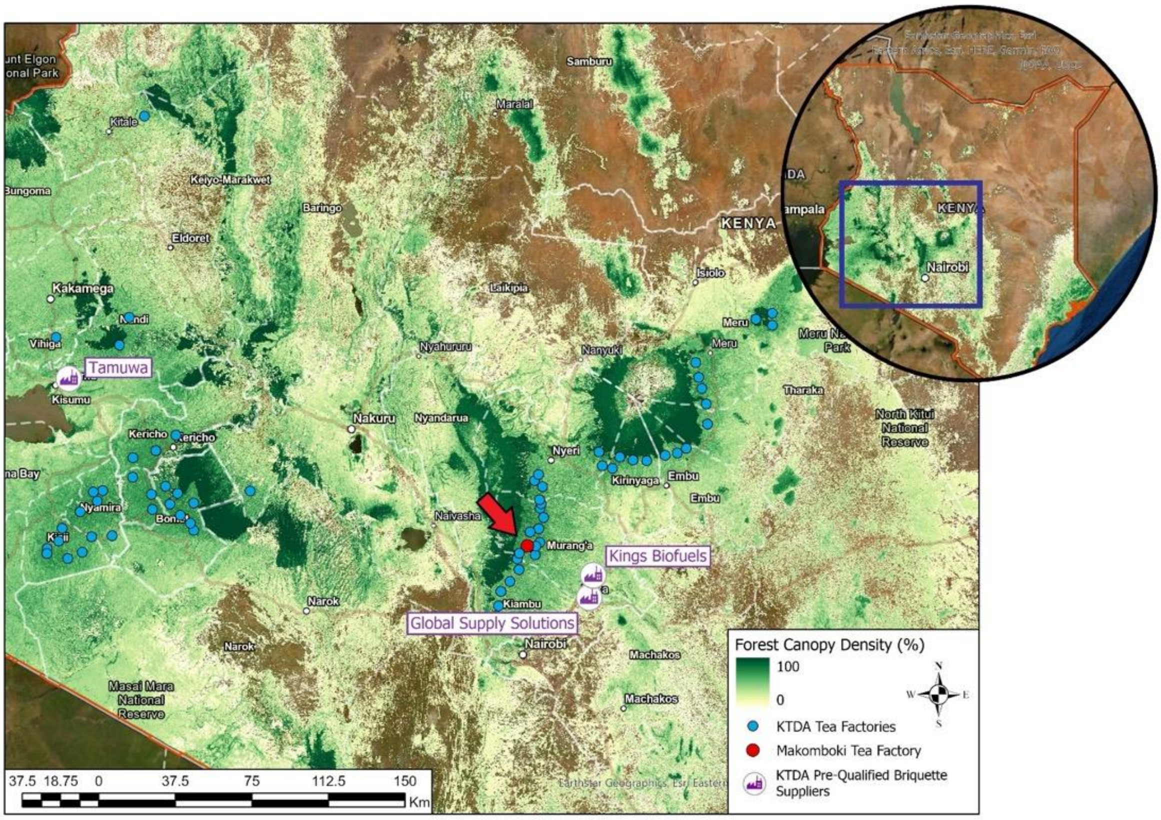


Figure 4-1. Map showing locations of KTDA tea factories and pre-qualified briquette suppliers (Source: authors' compilation)

All KTDA factories are Rainforest Alliance-certified and Makomboki is one of 27 that are also Fairtrade-certified.[8] The factory uses fuelwood for generating process heat and has been trialling the use of additional biomass fuels, as outlined below. Technical and operational details of the fuel sourcing and supply operation were kindly provided by KTDA staff, the Makomboki Factory management and the fuel supply companies mentioned, except where otherwise referenced. A selection of photos is in Appendix 6.

[8] www.ktdateas.com/our-markets/

4.2 Technical details

4.2.1 Plant design

Figure 4-2 illustrates the bioenergy supply chain and thermal energy system at Makomboki tea factory.

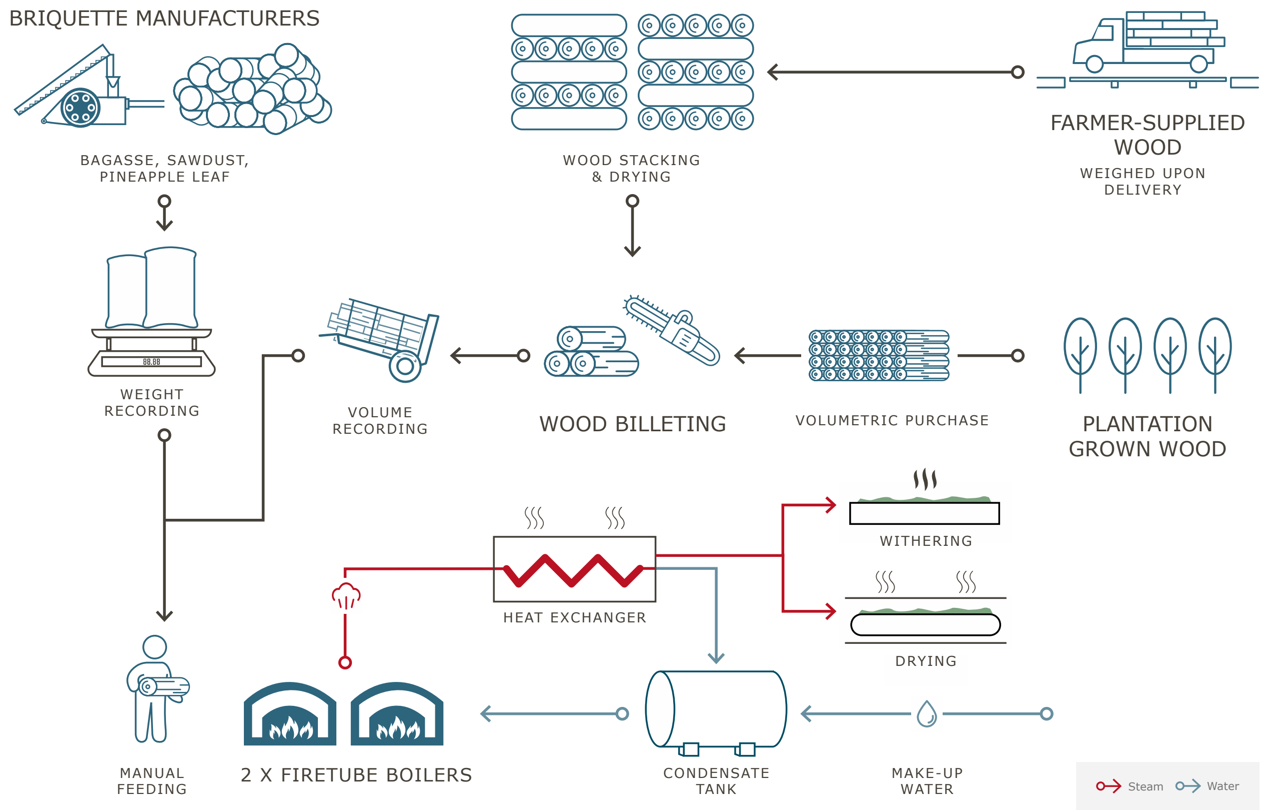


Figure 4-2. Schematic diagram of fuel supply and thermal energy system at Makomboki tea factory (Source: authors' compilation)

4.2.2 Fuel supply

Like all KTDA factories, Makomboki is mostly reliant on fuelwood. The factory sources mainly eucalyptus and *Grevillea robusta* from local farmers, many of whom are themselves tea growers and factory shareholders. It also buys wood from Kakuzi PLC, a large agri-business and forestry concern located 65 km to the east near Makuyu, as and when available. Makomboki itself has about 120 ha of tree plantations established to produce fuel, though these are not yet of harvestable age.

Fuelwood is purchased from farmers at KES 2,800 (USD 26) per stacked cubic metre (m^3) for eucalyptus and KES 2,400 (USD 22)/m^3 for grevillea. In accordance with KTDA policy, Makomboki applies a nominal weight-to-volume conversion of 750 kg per m^3, so the farmers are paid KES 3,733 (USD 34)/t for eucalyptus and KES 3,200 (USD 29)/t for grevillea, as measured on the factory's own weighbridge. This locally sourced wood is variable in size and quality, and tends to be freshly cut, with MC averaging over 50% upon delivery. MC is not measured, however, and there are no price adjustments for wetter or drier wood.

Kakuzi dries its fuelwood to 20% MC or less before sale. However, when fuelwood is purchased from small farmers and from other fuelwood sources, the MC can vary considerably. Makomboki has its own wood storage facilities. It tries to ensure that fuelwood, from whatever source, is as dry as possible, with a target set by KTDA as 25%, but, unfortunately, this is not always achieved, particularly when fuelwood is purchased from local farmers and others during the rainy season.

An estimated 20% of the factory's fuelwood is purchased from Kakuzi at a (March 2021) price of KES 3,290 (USD 30)/m^3 for eucalyptus and KES 2,975 (USD 27)/m^3 for grevillea.[9] Kakuzi's fuelwood is a by-product of its professionally-managed timber and pole operation, and yields evenly sized logs with low MC of around 20% (after a period of *in situ* drying). All prices are at farmgate, and do not include KTDA's costs of transport, handling, storage and preparation.

While the volumetric price of fuelwood purchased from farmers is lower than wood sourced from Kakuzi, the cost in energy terms is similar, at KES 499 (USD 4.60)/GJ from farmers and KES 529 (USD 4.90)/GJ from Kakuzi (for eucalyptus), due to the high MC of the locally sourced wood that offsets the volumetric cost saving.[10] The Kakuzi wood is also boiler-ready and of more consistent dimensions and quality. But it is not available consistently and has to be transported from further away at the factory's own cost, while the purchase of fuelwood from local farmers brings social and community benefits, especially as many suppliers and brokers are factory shareholders.

Properly drying fuelwood is key to increasing boiler efficiency and reducing smoke. It is recommended that fuelwood is dried to 15-20% for tea processing (International Trade Centre, 2014), although at KTDA factories the current target is 25% MC and wood is often wetter than this in practice. Assuming that Makomboki achieves the 25% MC target, cubic metre stacks at this MC will weigh 474 kg.[11]

The most effective way to dry fuelwood is to split it before stacking, ensuring space for airflow and natural ventilation. To prevent the wood from getting wet, it should be placed above the ground and kept under cover, with effective drainage (GIZ et al., 2019). The stacks should not exceed 4 m height with 1 m spacing (ibid.). Applying the 'first in, first out' principle, wood that was stored first should be the first issued to the boiler (GIZ, 2016). The wood should also be billeted[12] before use, to ensure efficient combustion and consistent steam supply. KTDA MS (Wood Department) specifies that fuelwood for boilers should be 1 m in length and 15 cm in diameter (G. Oselu, personal communication, 6 June 2020).

4.2.3 Biomass briquettes

Along with around 17 other factories in the KTDA system, Makomboki has been involved in the trialling of alternative fuels. One of these alternatives has been **briquettes**, made by compacting dry organic residues into densified logs. Makomboki initially piloted its own briquette production at the factory site. Through a connection made by Taylors of Harrogate, a customer in the UK, the Living Earth Foundation supplied a biomass dryer and ram press in 2015, with funding from the European Commission and British retailer Marks & Spencer (Langat, 2015). An enterprise was

[9] Kakuzi sells stacks of 1m x 3m x 1m height @ KES 9,870 for eucalyptus and KES 8,924 for grevillea, incl. VAT.

[10] Assuming 20% MC, 14 GJ/t and 444 kg/m^3 at Kakuzi, vs. 52.5% MC, 7.5 GJ/t and 750 kg/m^3 from farmers.

[11] A training manual developed for KTDA gives a density @ 20% MC of 394 kg/m3 for loosely stacked fuelwood and 493 kg/m3 for tightly stacked wood (GIZ et al., 2019). The average of 444 kg/m3 is taken as a realistic value, and extrapolated to 474 kg/m3 for wood at 25% MC.

[12] Billeting is the process of chopping the wood into smaller, regular sized pieces with increased surface area.

set up to produce briquettes from macadamia shell, cashew shell and rice husks, mixed with sawdust (Evans, 2015). Other forms of biomass were found unsuitable: coffee husks were light and hard to compact; rice husks had high ash content; and sisal briquettes formed clinker (EED Advisory, 2018).

The briquettes were expected to be cheaper than fuelwood and to burn more effectively, due to lower MC and higher heating value. It was initially reported that the use of briquettes had led to a 25% saving in the cost of fuel by running the boilers on a 50:50 fuelwood: briquette blend (Njenga et al., 2015). The Living Earth Foundation reported an annual cost saving potential of around KES 10 million (USD 140,000).[13] The project also delivered value for Marks & Spencer, by addressing their ambition to support communities in their supply chains (Rees, 2019).

Despite the promising start, the initiative encountered technical challenges. Briquette output proved insufficient to meet the needs of the factory, as the press produced only 200 kg/hr, against boiler demand of 800 kg/hr (Njenga et al., 2015). It also broke down frequently and it was difficult to obtain spare parts (EED Advisory, 2018). Other challenges included high MC in the feedstock, high cost of binders, inconsistent quality, contamination of tea with loose biomass and ash, and a lack of expertise and resources to run the briquette production line. Ultimately it became a question of organisational priorities, given that Makomboki's core business is tea processing, and the production of briquettes was terminated in 2017. The factory has since reverted to fuelwood plus supplementary briquettes (and sometimes macadamia nut shells), which are now purchased occasionally from outside suppliers.

In order to ensure consistent quality, quantity and price, KTDA organised competitive tenders for briquetted fuels in 2011 and 2019. 11 bidders responded to the first call and this resulted in three suppliers. The second call also attracted 11 bidders, with three producers shortlisted in late 2020 for briquettes made from sugar bagasse, sawdust and pineapple leaves (see text box). Fuel from these pre-approved suppliers may be purchased directly by the tea factories in the KTDA network at a standardised price, with confidence that it comes from competent, quality-checked manufacturers (although factories are at liberty to purchase from other companies if they wish).

[13] The briquettes produced by Makomboki with its donated machinery did not offer a sufficient basis for reliable comparison with purchased fuelwood or purchased briquettes. Biomass briquettes have proven to be a more expensive option for Makomboki than fuelwood, on a calorific value basis, as borne out by interviews with the Factory Manager in June 2020, a field visit in March 2021, examination of factory fuel purchase records and an independent economic analysis described below.

KTDA pre-qualified suppliers of biomass briquettes

Tamuwa Ltd operates a 2-line ram press briquetting plant on the edge of Kisumu, using bagasse from the nearby Kibos Sugar Factory to produce 90 mm cylindrical briquettes. The bagasse is pre-dried with a drum dryer. Production capacity is 40 t/day and is being upgraded to 160 t/day. The briquettes are 90% bagasse and 10% rice husk, with LHV of 18.8 MJ/kg and <10% MC. As of March 2021, Tamuwa supplies seven Unilever tea factories and has had 3 x 60 t orders from three KTDA factories since Dec 2020. Kibos has installed a paper plant that has affected bagasse supply, but the factory is expanding from 3,500 to 5,000 t/day of sugar cane, which should eliminate any supply challenges, despite the additional demands of the nearby White Coal and Lean Energy briquetting companies.

Kings Biofuels is located at Kenol, Murang’a and also produces 90 mm cylindrical briquettes using ram presses, made of sawdust and other loose biomass such as coffee husk. Its twin production lines have a capacity of 40 t/day and the company sells up to 200 t/week to non-tea sector clients, but by March 2021 had not received any orders from KTDA factories. Its briquettes have LHV of 17.5-18.4 MJ/kg, depending on the type of sawdust, with 8% MC and 4.9% ash. A dryer is used to prepare the sawdust for densification. Frequent power outages are a significant impediment to production.

Global Supply Solutions is located close to the Del Monte pineapple estate near Thika, from where it sources pineapple leaves for briquetting. The leaves are dried in the fields until MC reduces to around 15%, and MC is further reduced to 11% through milling and finally to 9% when rammed to form briquettes. Global Supply has a state-of-the-art 4-line plant with Danish machinery in a custom-built facility, with a production capacity of 150 t/day. Its 70 and 90 mm briquettes have LHV of 17.8 MJ/kg with 9-11% MC and 4% ash. It has so far not had any orders from KTDA factories.

Briquettes from the pre-qualified suppliers are priced at KES 15,660 (USD 144)/t (incl. VAT), with a typical LHV of 18 GJ/t at 10% MC, giving an effective cost of KES 870 (USD 8)/GJ. This is 65-70% higher than the fuelwood cost of KES 499 to 529/GJ (USD 4.6 to 4.9) (see above).

The blunt metric of unit energy cost does not consider some of the non-financial advantages of briquettes compared with fuelwood. For example, these fuels are boiler-ready upon delivery, have lower MC and higher calorific value, are easier to handle and account for, and deliver predictable performance with consistent steam yield. Nevertheless, there is still a significant price differential between fuelwood and briquettes. This is presumably the reason why the contribution of briquettes to total energy supply at Makomboki declined from 16.5% in 2018 to 9.5% in 2019 and 4% in 2020. On average, between January 2018 and December 2020, Makomboki blended 7.7% bagasse briquettes with 92.3% fuelwood, on an energy basis.[14] The factory is currently using up old briquette stocks and has not made any recent purchases.

Since the confirmation of the three pre-qualified suppliers in late 2020, it is understood that only three KTDA factories have so far purchased briquettes, all of which have come from the same supplier. VAT on briquettes was removed on 30 June 2021 (Republic of Kenya, 2021). Although early market indications are that briquette companies have generally retained the same end prices to customers, it is too early to tell what effect this will have on the sale of briquetting machinery and briquettes themselves.

4.2.4 Other biomass fuels

In addition to its purchases of fuelwood and briquettes, Makomboki has sometimes sourced macadamia shells from local nut processors. These are a desirable source of

[14] Total energy use 2018-2020 was 63,304 m^3 of fuelwood with an estimated 474 kg/m^3 and 13 GJ/t (@25% MC), plus 1,816 t of briquettes with 18 GJ/t (@10% MC), for a a total of 32,690 GJ from briquettes and 390,079 GJ from fuelwood.

energy due to low MC and high calorific value (19.6 GJ/t, dry basis [d.b.]). The shells can be used directly in loose form. The main challenge is seasonality (7 months per year) and the competing demands of other industries, such as edible oil refineries, which have pushed up prices from KES 5,000 (USD 46)/t in 2017 (EED Advisory, 2018) to as much as KES 16,000 (USD 147)/t in 2021.

Cashew shells are cheaper than macadamia shells, but are less favoured owing to their corrosive characteristics resulting from high acid content (EED Advisory, 2018). Sawdust can also be purchased from numerous small sawmills for KES 1,000/t (wet weight). Sawdust is also generated during fuelwood re-sizing at tea factories and could potentially be sufficient to meet 1.5 to 1.7% of total thermal energy requirements (Inoti, 2016). Tea fluff and sweepings have been considered as additional sources of thermal energy, but the available quantities are small and the total energy potential from these wastes is only around 0.1% of typical factory requirements (ibid.). Rice husks were trialled but discontinued due to high ash content.

4.2.5 Boiler operation and maintenance

The boiler is the heart of the thermal energy operation at a tea factory. Given that 90% of factory energy requirements are for heat used in withering and drying, maximising boiler efficiency can significantly reduce energy requirements and production costs (GIZ, 2016). Most KTDA factories are equipped with horizontal, 3-pass firetube boilers[15] that produce low pressure steam (GIZ et al., 2019). Makomboki has two wood-fired boilers operated at 600°C, each producing 3 t/hr of steam at 160°C and 9 bar pressure. An older, oil-fired boiler was last used more than 10 years ago.

The boilers are fitted with preheaters to bring the combustion air to between 120 and 170°C, and the steam system is fully insulated to eliminate heat loss. These two measures alone can cut fuelwood consumption by about 5% (KTDA, 2020b). The boilers are ideally fed only with billeted wood, ideally chopped into billets measuring 15 cm by 25 cm, placed into a wood cage for proper measurement for feeding to the boiler (GIZ et al., 2019). Feeding should take place through one door, which is then closed. Wood is pre-measured in a hand cart (and briquettes on a flatbed scale), to facilitate record-keeping. The boilers are run at full capacity where possible, and excessive blow-down is avoided.[16] The flue gas temperature is monitored, with a target range of 180-220°C (higher than the optimal 120-160°C). No leaf is delivered to the factory on Sundays, giving an opportunity for routine maintenance during an 8-hour shutdown every Monday, when the boiler tubes and heat exchange tubes are brush-cleaned, and the steam lines and traps are checked for leaks. Safety compliance audits are undertaken annually by certified inspectors from the Directorate of Occupational Safety & Health Services.

The boilers can burn briquettes and loose fuels without modification, up to a blending ratio of around 30%, with operators advised to feed fuelwood at the bottom and loose biomass on top - though this is not an ideal work-around and the introduction of

[15] A firetube (or smoke tube) boiler passes combustion gas inside a series of tubes surrounded by water in a vessel to produce steam, whereas a water tube boiler sends water through a series of tubes surrounded by combustion gas used to transfer heat energy and produce steam. Water tube boilers operate at higher temperature and pressure, so are more suitable for CHP applications.
[16] Boiler blowdown is the intentional wastage of water to avoid concentration of impurities in the steam.

movable grates would be preferable to address clinkering and small particle size. Makomboki reports that the quality of bagasse briquettes has been improving over time, after early problems with clinkering, and they are happy with the performance of the briquettes currently available.

The thermal energy requirement at Makomboki is 22.7 GJ per tonne of MT, based on three years of data on tea output and fuel consumption.[17] Makomboki also uses 0.55 KWh (2 MJ) of electrical energy per kg MT, for a total energy intensity of 24.7 GJ/t MT. This is around 19% higher than the KTDA target of 20.8 GJ/t MT (GIZ et al., 2019), and 12% higher than Makomboki's own efficiency target of 22 GJ/t MT (Factory Manager, personal communication, 10 March 2021).

4.2.6 Technology sourcing and costs

The Technical Services Department at KTDA headquarters procures capital equipment and provides technical guidance to the network of factories, while regional engineers work closely with factory technicians to implement, operate and maintain the plants. A stock of fast-moving spares is procured and kept at each factory.

In the early years of Africa's tea industry, steam boilers were mostly supplied from the UK (e.g. Marshalls) or from India (e.g. Yule). Boiler technology is now more widely available and equipment tailor-made for either solid biomass or loose biomass can be sourced from a variety of manufacturers in a greater number of countries. For example, John Thompson (South Africa)[18] offers a 'SIMPAC' wood-fired boiler with a fixed grate in three sizes and a 'Torripac' hybrid biomass boiler designed for pellets, briquettes and loose biomass. ISGEC (India) has supplied 27 boilers to agri-businesses in Africa.[19] There is growing competition from Chinese suppliers, such as Zhengzhou Boiler Group, which has supplied tea factories in Kenya.[20] KTDA sources its boilers centrally from two main suppliers, John Thompson (South Africa) and Thermax (India).[21] Both of the boilers at Makomboki are 'Woodpac' units from Thermax.

The Kenyan engineering firm J.F. McCloy[22] now also manufacturers steam boilers and dominates the supply of ancillary equipment to the tea industry across East Africa, including withering troughs, fermenting machines, fluidized bed dryers, sorters, heat exchangers and fans.

Engineering expertise in this area is therefore well developed, with suitable machinery and support available from both local and international suppliers.

4.3 Economic assessment

Table 4.1 summarises the data used in the LCC model for Makomboki, substituting a portion of its fuelwood with briquettes (as the Bioenergy Case), compared with a Base Case scenario of generating heat using fuelwood only. The Bioenergy Case assumes that 8% of energy comes from briquettes, which reflects the reality at Makomboki for the 3-year period 2018-2020.

[17] Over the 3-year period Jan 2018 to Dec 2020, average annual factory output was 6,203 t of MT and fuel use averaged 21,101 m^3 of fuelwood (calculated to be 10,002 t @ 25 MC, 474 kg/m^3, 13 GJ/t) plus 605 t of bagasse briquettes (at 10% MC, 18 GJ/t). Thus, total energy input of 140,923 GJ for 6,203 t of MT, which is 27 GJ/t MT.

[18] www.johnthompson.co.za

[19] www.isgec.com/boilers/ba-boilers-overview.php

[20] www.zgboilers.com

[21] www.thermaxglobal.com

[22] www.jfmccloy.co.ke

Table 4.1: Key project data for economic modelling

Category	Parameter	Value
General parameters	Discount rate	10%
	General growth rate	8% (Consumer Price Index)
	Energy price growth rate	8% (Energy Price Index)
	Electricity price	USD 152.44/MWh_e (Kenya Power Small Commercial tariff)
	Exchange rate	102.33 KES/USD (3 yr average)
Base Case	Energy intensity	22.7 GJ/t MT
	Tea output	6,252 t/year
	Fuel used	Fuelwood. LHV 13 GJ/t @ 25% MC
	Fuel cost	80% locally supplied @ USD 63/t (USD 62 + USD 1 for handling and preparation). 20% from Kakuzi or similar @ USD 79/t (USD 64 + USD 15 for transport). Fuelwood prices levelised to 25% MC.
Bioenergy Case	Biomass substitution rate	8% briquettes (plus 74% fuelwood from farmers; 18% fuelwood from Kakuzi)
	Feedstock used	Bagasse briquettes: LHV 18 GJ/t @ 10% MC. Fuelwood properties as per Base Case.
	Feedstock cost	Bagasse briquettes: KES 15,660 (USD 153)/t plus USD 15/t for transport = USD 168/t. Fuelwood costs as per Base Case.

Applying these input parameters, the LCC model shows that the Makomboki tea factory has lower LCOE for heat under the Base Case than the Bioenergy Case (Figure 4-3 below), being USD 50.2 per MWh_{th} against USD 53.9 per MWh_{th}. The current level of partial substitution of fuelwood by briquettes thus results in a 7.4% cost increase in the cost of thermal energy.

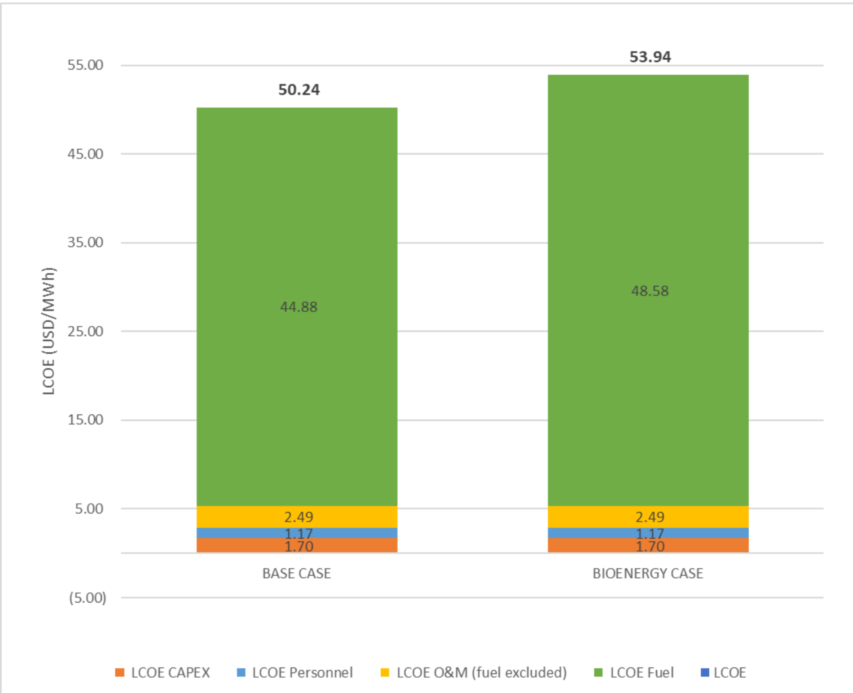


Figure 4-3: LCOE comparison for Base Case vs. Bioenergy Case, Makomboki tea factory

4.4 Commercial factors

Figure 4-4 summarises the key elements of the Makomboki fuel supply chain.

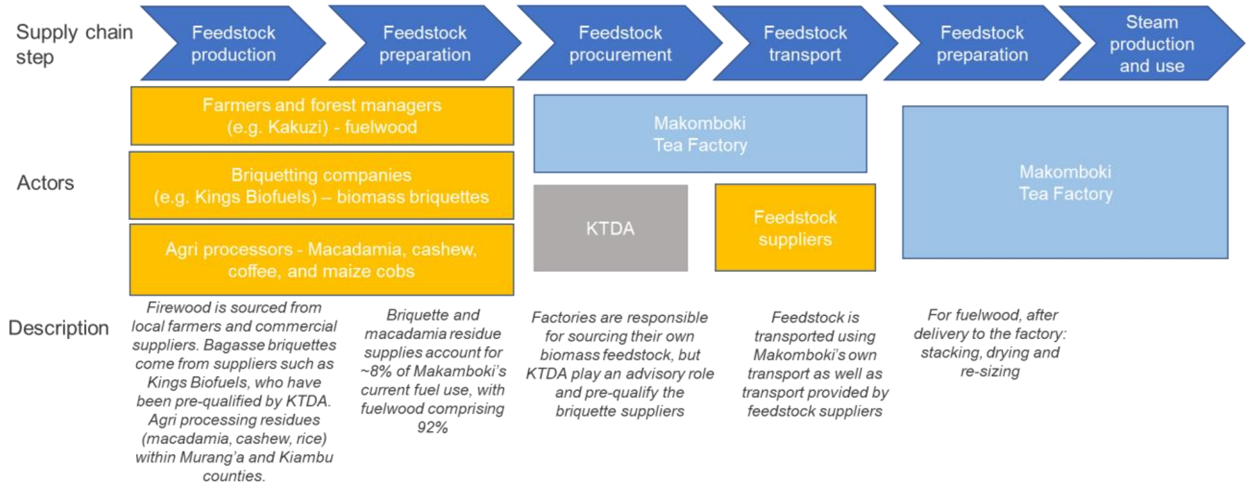


Figure 4-4: Overview of the Makomboki supply chain

Energy represents 24% of the cost of tea production at Makomboki (KES 21.5 out of KES 89/kg MT). In common with many similar factories, this provides the management with a strong motivation to reduce fuel costs and improve energy efficiency. While the cost comparison between energy from fuelwood and a blend of fuelwood and briquettes is not favourable, as the preceding economic analysis has shown, there are nevertheless a number of commercial considerations that may have motivated Makomboki and other factories to trial the use of alternative biomass fuels:

a) **Market expectations:** KTDA factories strive to respond to market sustainability concerns in a practical way. The supplementary use of non-fuelwood biomass helps meet the expectations of the Rainforest Alliance, Ethical Tea Partnership, Fairtrade certification and premium markets, which are vital for Kenyan smallholder tea.

b) **Fuel supply security:** Acquiring a reserve stock of briquettes can help bridge periods of seasonal fuelwood shortage or supply chain problems (e.g. caused by impassable roads during rainy seasons). The fact that briquette use at Makomboki has risen and fallen in approximate proportion to tea output suggests that this may have been a motivating factor for their purchase.

c) **Fuel supply diversity:** Makomboki's own fuel plantations are small and not yet mature, so the factory relies on third party wood suppliers. It makes commercial sense to keep the fuel supply base diverse for security of energy supply, and to include non-fuelwood suppliers in the mix.

d) **Fuel supply future-proofing:** KTDA has helped its factories to experiment with the sourcing of novel fuels and to explore boiler tolerances for alternative fuels. With reliable performance data on a number of alternative fuels, factories are well prepared for future market shocks that might affect fuelwood supply.

e) **Fuelwood price stabilisation:** Having a number of pre-qualified suppliers of fuels other than non-fuelwood wood may provide a 'bargaining chip' for Makomboki and other KTDA factories to keep prices low.

f) **International partnership opportunities:** Being open to innovation and new ways of improving fuel management and efficiency means that KTDA factories can access a variety of training and practical support for factory staff and their shareholder communities. A number of development initiatives have in the past been supported by GIZ, IKEA Foundation, Gatsby and others, and these have sometimes included alternative fuel trials.

5 Potential for wider adoption

This section assesses the replicability potential of the Bioenergy Case in the tea processing sector, considering the six research themes of biomass resources, technology, economic benefits, commercial potential, the institutional and regulatory framework and gender and inclusion.

5.1 Biomass resource assessment

5.1.1 Biomass potential for briquetted fuels for tea factories

For every hectare of planted tea, about 0.25 ha of fuelwood plantation is required (ESD, 2005). In the case of Kenya's tea production about 60,000 ha of land to harvest fuel wood would be required per year, considering about 240,000 ha under tea production (FAO, 2021a). With fuelwood production ranging between 3 to 5 years, 180,000-300,000 ha of short-rotation plantations is required to meet the needs of the tea industry. With only 220,000 ha of planted forest under public and private ownership (FAO, 2021a), this can result in significant sustainability challenges. The tea industry is therefore looking for alternative sustainable fuel sources and is already tapping into biomass residues resources.

Agriculture is the main economic sector in Kenya, contributing 26% to GDP and employing over 40% of the population (and 70% of the rural population) (FAO, 2021a). Tea is the main commercial crop, and other important crops include sugarcane, maize and roots and tubers (potatoes, cassava and sweet potato), as well as fruits (led by banana and mango) and vegetables (led by beans and cabbage) (Figure 5-1).

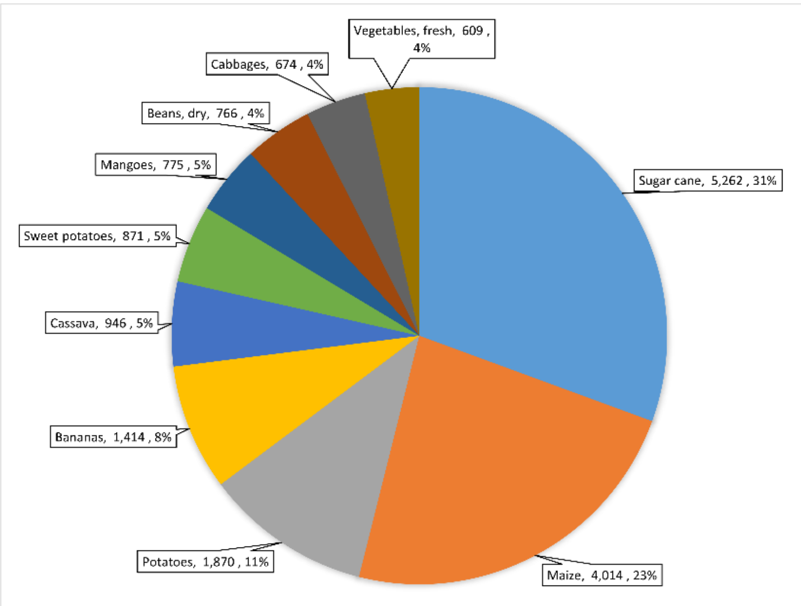


Figure 5-1 Top-10 crops in Kenya, kilo-tonnes (kt) and percentages per year (FAO, 2021a)

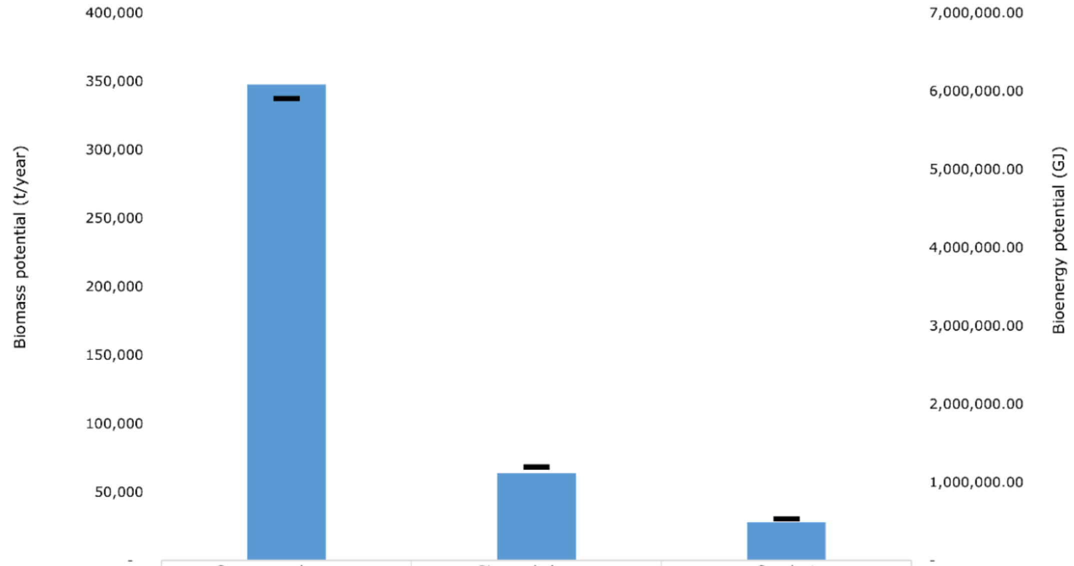
For producing briquetted fuels for the tea sector, there are a number of potential biomass feedstocks from agricultural and processing residues.

Maize residues and cassava stalks have suitable properties for combustion applications, but setting up supply chains would be challenging as these crops are mainly grown by small-scale farmers and the residues are not aggregated in tea growing regions.

Sugarcane bagasse is a more attractive feedstock with conducive properties for thermal applications and centralisation at sugar mills. While Kenyan mills use some bagasse for their own energy supply, many have surpluses that could be used to produce briquettes (UNEP et al., 2019). Pineapple leaves are an additional residue available in smaller quantities, but have favourable properties and low MC (ibid.)

Other feedstocks used by small numbers of KTDA factories (including Makomboki), directly or in densified (briquetted) form, include sawdust and macadamia and other nut shells (EED Advisory, 2018). Nut shells face seasonality constraints and there is high demand from other industries due to favourable combustion characteristics (EED Advisory, 2018; ESD, 2005). Rice husk can be sourced from milling operations, but is difficult to use in tea factory boilers due to high silica content, leading to glassing and slagging.

For the purposes of estimating resource availability, it is assumed that the removable fraction of biomass is 40% for bagasse and sawdust, and 80% for pineapple leaves, though these may differ in reality, due to other uses, losses and supply chain economics. Figure 5-2 summarises the biomass and bioenergy potential from these feedstocks, as potential raw materials for fuel briquettes. The assessment reflects the high potential of sugarcane bagasse, which is already a key feedstock in briquetting. A number of additional feedstock resources (e.g. maize stalks and cobs, wood processing residues and nutshells) are detailed in Appendix 3, which could be blended with bagasse, sawdust or pineapple leaves, depending on local availability, suitability and cost. These three feedstocks can provide about 439,000 t of biomass (dry basis) with an energy potential of 7.6 million GJ per annum.



	Sugar cane bagasse	Pineapple leaves	Sawdust
Biomass potential (t dry basis)	347,302	63,596	27,972
Bioenergy potential (GJ)	5,904,140.15	1,195,613	531,468

Figure 5-2. Biomass and bioenergy potential for selected feedstocks

While adopting alternative sources of biomass is important for the energy security of the tea industry, and represents the Bioenergy Case being trialled at Makomboki and other tea factories, it is equally important to improve the short- and long-term sustainability of fuelwood sourced for the tea sector and other industrial uses. Yields vary by species and genotype with some *Eucalyptus spp.* very fast-growing with potential annual increments of 10-20 m^3/ha, and indigenous *Acacia spp.* and legume trees like *Gliricidia sepium* with annual increments from 6-10 m^3/ha (FAO, 2000). With 3-6 year coppicing cycles, stumps can be left in the ground for 25-30 years (Kenya Forest Service, 2009). However, such establishment should not impact naturally regenerated woodland and forests or agricultural land.

Utilising marginal land for small-scale forestry can support soil and watershed remediation, sustain biodiversity and support wider ecosystem services (Eufrade-Junior et al., 2018; FAO, 2000, 2009; Kenya Forest Service, 2009), though biomass yields are likely to be sub-optimal on such land. Moreover, any type of land use change and restoration requires a careful assessment of environmental and social impacts, land use and land access. Many farm households also have standing trees on their farms to produce fuel or fruit, and research has indicated that farmers are interested in improving small-scale wood production for commercial use, if there is a reliable market and price (ESD, 2005; Rees, 2019). The integration of woodlots with indigenous species can provide opportunities for intercropping and agro-forestry, may offer fruits that are used as food or medicine, and can support biodiversity and eco-system services. Managing such integrated woodlots can support revenue for households from wood sales (Arnold & Dewees, 2014; Eufrade-Junior et al., 2018). Such efforts would benefit greatly from more support to small-scale commercial forestry for multiple products, including commercial fuelwood. This could include access to better quality seed and seedlings, extension support for optimal management, deregulation of the harvesting and transport of farm-grown wood, and credit schemes to incentivise forestry investments as a long-term source of revenue and livelihood support.

5.1.2 Mass-energy balance

Table 5.1 shows the mass-energy balance (MEB) parameters for using biomass to cover the thermal energy demand for tea processing. The input data are based on the specifications of the Makomboki factory.

Table 5.1: Mass-energy balance, bioenergy for heat in tea processing

Parameter	Units	Value
Biomass feedstock	Fuelwood:briquette ratio	92:8
Input Parameters		
Target capacity	MW_{th}	2 x 2.0
Capacity factor	%	90
Annual operation	hours	7,884
Process	Drying and withering	
Fuelwood substitution by briquettes	%	8
Efficiency	%	80
Specific thermal energy consumption	MJ/kg of made tea	22.7
Fuelwood calorific value	MJ/kg	13
Fuelwood MC	%	25
Briquettes calorific value	MJ/kg	18

Parameter	Units	Value
Briquettes MC	%	10
Output of MEB model		
Biomass flow total	kg/s (d.b.)	0.34
	annual tonnes (d.b.)	9,606
Fuelwood flow	kg/s (w.b.)	0.35
	annual tonnes (w.b.)	10,043
Briquette flow	kg/s (w.b.)	0.02
	annual tonnes (w.b.)	631
Made tea	Annual tonnes	6,252

Figure 5-3 shows the results of the MEB model based on the input specifications of the Makomboki tea factory, indicating biomass flows and energy production, including losses. Considering a fuelwood substitution rate of 8% by biomass briquettes suggests a briquette requirement of 631 t/yr and a fuelwood demand of 10,043 t/yr (both wet basis [w.b.], briquettes @ 10% MC, fuelwood @25% MC). 100% substitution of fuelwood with briquettes would require 7,884 t of briquettes per year (w.b.), to deliver the same amount of energy and made tea.

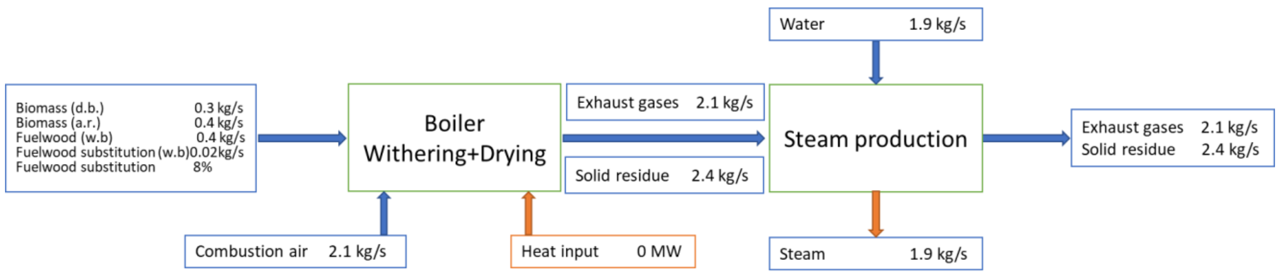


Figure 5-3: Mass-energy balance for heat generation for tea processing, based on Makomboki input specifications

A factory of the scale of Makomboki, producing around 6,200 t of MT per year, requires a thermal energy input of around 140,000 GJ. The biomass resource assessment has shown that the residues already used for briquette production, such as bagasse, sawdust or pineapple leaves, are more than sufficient to meet this demand. Bagasse alone could potentially provide 5.9 million GJ/annum. With one tonne of made tea requiring about 22.7 GJ/t of thermal energy (based on Makomboki data), bagasse briquettes alone could provide sufficient energy for the production of ~260 kt of MT annually, which is about 60% of Kenya's tea production. Biomass resource availability is therefore not considered a constraint to the wider adoption of briquetted fuels in this sector.

5.2 Technology

Steam boilers and ancillary equipment for the black tea industry are available from both local and international suppliers, well adapted to the use of seasoned wood. KTDA factories have many years of experience in operating this robust equipment, which is mostly sourced from Thermax (India) and John Thompson (South Africa), ensuring that operating expertise is well developed within factory staff and regional engineering support teams, and there is sufficient demand to ensure reliable access to spares, replacements and manufacturer support. Procurement, operation and maintenance of these well-tested pieces of equipment presents no impediment to further development of the use of bioenergy in the Kenyan smallholder tea sector.

Briquettes can theoretically replace fuelwood, using existing boilers, heat exchangers and steam circulation systems. Moveable grates would ideally be required, to address clinkering, together with more frequent removal of ash. Automated briquette feeders would be a progressive addition to allow close monitoring and control of fuel feeding. As briquettes have not been adopted at scale for economic reasons, such modifications to furnaces and fuel feeding systems have not been necessary. At blending ratios of 20% or less, it has been possible for KTDA engineers to train operating staff in the management of blended fuels, without investing in new equipment. But there is no technical obstacle to customisation for greater briquette feeding ratios with briquette manufacturers advising more optimal fuel management and avoidance of clinkering at much higher rates of briquette use. There are also dedicated boilers on the market that can operate with 100% briquettes, pellets or loose biomass residues. But again, for reasons of fuel cost, KTDA factories have not considered it justified to investing in equipment replacements of this nature.

5.3 Economic viability

The economic viability of the partial substitution of fuelwood by biomass briquettes is influenced by many factors, such as the price of both fuels and the substitution rate. In this section, the impact of these parameters on $LCOE_{heat}$ is estimated through sensitivity analysis. In each of the charts below, the linear regression lines are a best-fit for the results from hundreds of simulated scenarios.

Figure 5-4 shows the sensitivity of LCOE to a fuelwood substitution rate ranging from 0% to 30% (compared with the Makomboki rate of around 8% over the last three years). Increasing the percentage of substitution naturally increases the LCOE of thermal energy for all the scenarios, since the cost of energy from briquettes is higher than that from fuelwood.

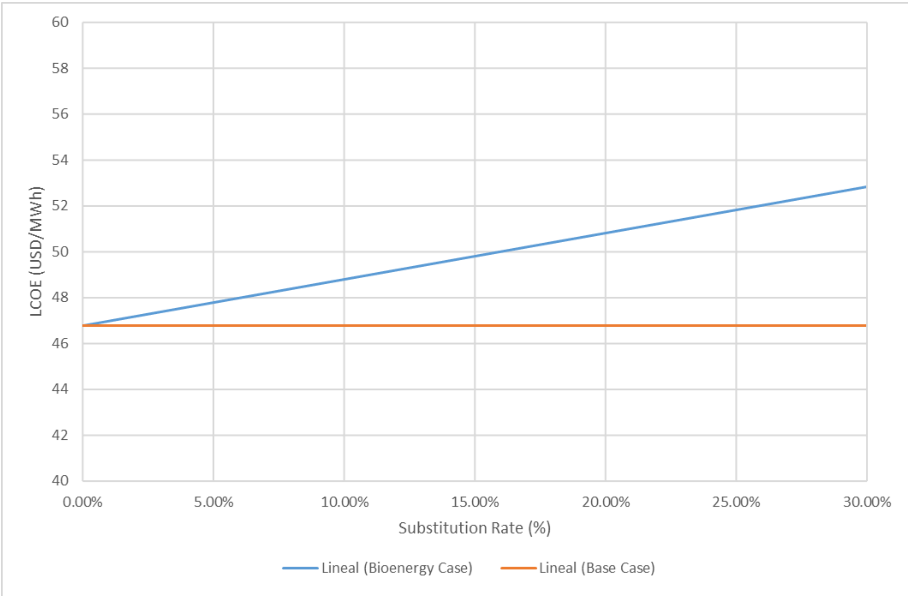


Figure 5-4: Sensitivity of $LCOE_{heat}$ to fuelwood substitution rate from 0% to 30%

Figure 5-5 shows the sensitivity of LCOE to a range of briquette costs from USD 50-175/t (versus a current cost of around USD 168/t), under a number of operational scenarios (substitution rate from 0% to 30%, reference feedstock cost from USD 40/t to USD 80/t, and capacity factor from 60% to 100%). The analysis shows that the tipping point of viability is achieved at a briquette cost of around USD 75/t, including delivery costs, which is substantially lower than the current cost.

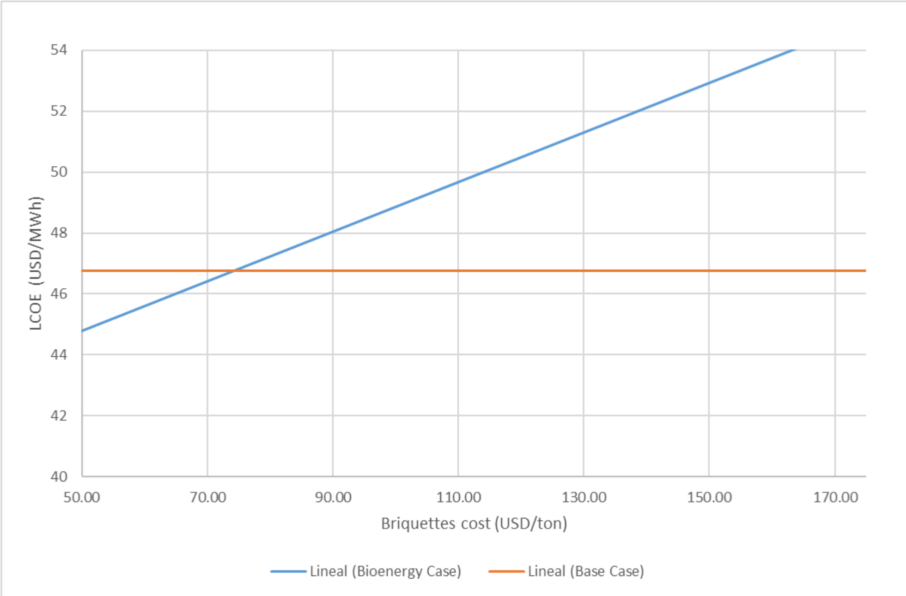
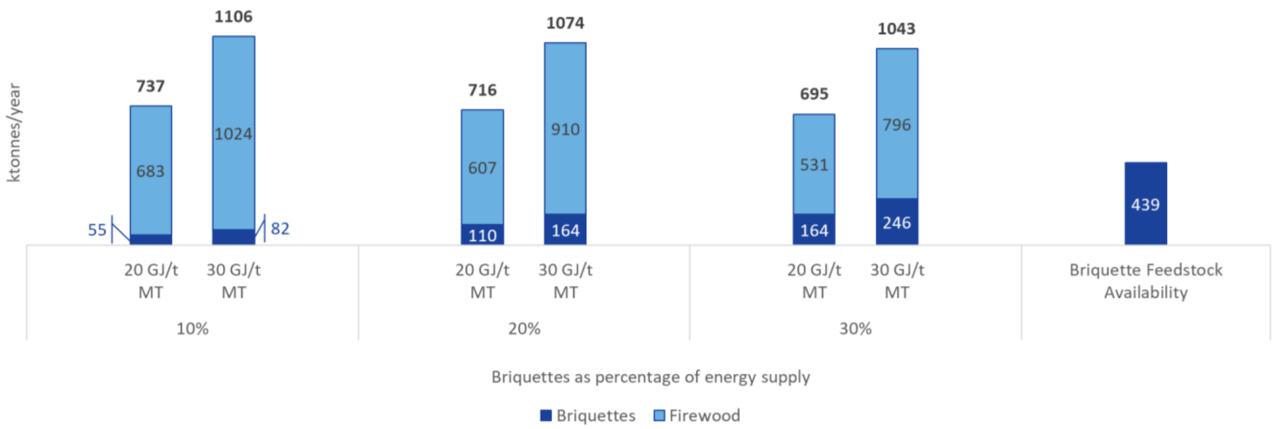


Figure 5-5: Sensitivity of $LCOE_{heat}$ to briquette cost

5.4 Commercial prospects for replication

5.4.1 Market potential

Kenya's tea production doubled over the 20 years to 2019, to reach about 439 kt p.a. (FAO, 2019; Kenya Tea Directorate, 2021). This growth is expected to continue, and will have a direct influence on the demand for thermal energy in tea processing. The potential biomass demand from the sector is shown in Figure 5-6, and compared with the biomass resource assessment from Section 5.1. Three scenarios have been modelled for blending fuelwood with briquettes, at 10%, 20% and 30% of total thermal energy supply. As energy intensity can vary significantly between factories, for each scenario a low-end demand estimate is made assuming 20 GJ_{th}/t MT and a high-end using 30 GJ_{th}/t MT.



[left column = low demand scenario (20 GJ_{th}/t MT); right column = high demand scenario (30 GJ_{th}/t MT)]

Figure 5-6: Comparison of potential non-fuelwood biomass demand in the Kenyan tea sector with feedstock availability, for different briquette blending rates.

The potential market size for briquettes for tea processing varies from 55 to 246 kt/yr across the scenarios. This is well within the total feedstock availability of 439 kt/yr (dry basis) for the three leading resources, even allowing for some losses during briquette manufacture. While the current production capacity of the three KTDA pre-qualified suppliers is only around 80 kt/yr,[23] at least one of them is planning a significant equipment upgrade, and there are a number of additional suppliers who can between them supply at least double the maximum capacity of the existing approved suppliers.[24] There is also substantial residue feedstock potential from maize, cassava, rice and macadamia/cashew crops (roughly ~700 kt/year) which could be accessed for blending with the three primary feedstocks, though adoption potential is likely to be lower due to issues of cost, aggregation and suitability. In summary, however, there are no significant supply-side barriers to increased briquette production, with ample feedstock available and most producers operating below capacity.

5.4.2 Market barriers

The key barriers and enablers that will determine the viability of the more widespread use of biomass residues in the tea sector are summarised in Table 5.2 below.

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

Barrier to business model	Enabling conditions
Increased demand for feedstock, and feedstock cost: There has been increased competition from other tea factories and other commercial sectors (e.g. edible oil producers) for high-grade biomass residues such as macadamia shells and coffee husks, which has increased prices and led to a drop-off in use by tea factories. For other feedstocks that need to be pre-dried, especially bagasse and sawdust, there seem to be no major supply constraints at present. Increased competition for feedstock is not, therefore, expected to present a constraint to briquette output at current levels of use, or reasonable future projections.	**Focus on bulk, aggregated briquetting feedstocks:** Despite shortages of some types of high-grade biomass residues, industrial scale producers of residues, such as sugar mills, sawmills and agri-businesses, are still able to guarantee supply to large-scale off-takers such as briquetting companies. With a commitment to regular, bulk purchasing, briquette manufacturers can ensure low feedstock pricing and supply chain reliability.
Sourcing cost competitive biomass residues and briquettes: Individual KTDA factories may not have the resources, knowledge or capability to find cost competitive biomass residues and briquettes of suitable quality.	**Centralised organisation to facilitate feedstock sourcing and purchase:** KTDA plays an important intermediation and coordination role in advising individual tea factories, and in pre-qualifying reliable and well-capacitated briquette suppliers.

[23] Current annual capacity is 50,000 t from Global Supply Solutions, 14,600 t from Tamuwa and 14,600 t from Kings Biofuels, with Tamuwa planning to upgrade to almost 60,000 t.
[24] Additional suppliers include White Coal and Lean Energy near Kibos Sugar Mill in Kisumu, and Vuma Biofuels at South Nyanza Sugar, Migori.

Barrier to business model	Enabling conditions
Higher overall costs of alternative biomass fuels Fuelwood is a cheap energy source, at least 30% cheaper (per GJ) than briquettes, albeit with a requirement for drying and preparation prior to use.	**Addresses sustainability concerns around fuelwood use:** There is a perception that using fuelwood is less sustainable than using biomass-based briquettes (though it is not clear whether there is sufficient evidence to justify this perception). This creates a driver for tea factories to demonstrate sustainable sourcing of briquettes for energy consumption.
	Diversification of supply helps to keep fuelwood costs down: Use of residues and briquettes provides a 'bargaining chip' to keep fuelwood prices low across the KTDA system, by having alternatives that can be brought on-stream quickly. This helps manage the overall cost of energy production at the tea factories.
	Wider benefits could be available to tea factories: Using residues and briquettes shows that tea factories are prepared to innovate and are open to the ideas of international buyers and development partners, which may have wider benefits as part of more comprehensive support, training or funding packages.

5.4.3 Finance

Each KTDA factory is financially independent. While KTDA provides significant guidance and technical support, decisions on processing equipment, thermal energy supply and fuel sourcing rest with the majority shareholders, who are mainly local tea farmers. If alternative fuel choices make commercial sense, then the shareholders are likely to approve them. Machinery upgrades are not required up the 30% blending level targeted by KTDA, so raising capital to adopt non-fuelwood biomass is not a barrier to replication. Additional capital would only be required for a full switch away from fuelwood, as this would necessitate changes to the boilers, grates and feeding systems. This is a highly unlikely scenario, given the economic and commercial constraints discussed.

5.4.4 Summary of commercial prospects

The use of alternative forms of biomass energy by smallholder tea factories in the KTDA network has a number of commercial benefits that might motivate those factories to consider their use to supplement fuelwood. As outlined in 4.4 above, such motivating factors may include market expectations, the need to ensure that fuel supply is diverse, secure and stable, and the part that such innovations can play in building functional relationships with supportive development partners. But the economic analysis and evidence from the remote consultations and site visits suggests that these motivating factors are not sufficiently strong to drive the replication of this business model.

KTDA pre-qualified briquette producers in 2011 and again in 2019. The latest selected bidders (3 active briquette producers - one bagasse, one pineapple residue and one wood residue) are available to sell briquettes at prices agreed by KTDA MS. Thus far, these current briquette companies have sold little or no fuel to KTDA factories.

This is not an issue of raw material supply or production capacity at the low volumes at which they are currently operating. There is ample bagasse, sawdust and pineapple residues and other potential feedstocks for these (and other) producers to significantly ramp up production, if the factories wanted to buy in greater volumes. It is simply that demand from tea factories is insufficiently strong, with at least 55 out of 70 tea factories never having used briquettes, despite the support that KTDA has provided in identifying credible manufacturers with sufficient production capacity.

As noted, briquettes are currently around twice as expensive as fuelwood on an energy basis, and the cost of producing heat in the Bioenergy Case is significantly higher than the Base Case. The benefits of feedstock diversification are currently insufficient to overcome the cost differential, and there has thus been only limited uptake of briquettes across KTDA factories. While the removal of VAT from briquette manufacturing machinery and briquettes is a step in the right direction, unless there is a very significant change in relative fuel costs, this suggests limited replication potential within KTDA factories.

5.5 Gender and inclusion

Despite relatively high rates of engagement and employment of women, Kenya remains blighted by gender inequality, including in the agricultural sector. Although women account for about 80% of farm labourers and run over 40% of smallholder farms, they only own 1% of the agricultural land (Kimani, 2020), creating disadvantages in reaping benefits from livelihood activities such as tea growing or fuelwood production. The Government has not created significant incentives to improve gender and social inclusion, with the revised 2010 Constitution failing to deliver transformations on this issue (ibid.).

When considering G&I issues in energy supply in the smallholder tea sector, it is important to address the supply chain from farmer level through to the factory. A key barrier for the engagement of women in both tea production and in farm forestry (including for fuel) is the lack of access to finance (including on productive assets), inequitable land ownership and under-representation in senior decision-making roles within the tea industry. At the farmer level, while there are usually a greater number of roles conducted by women in the tea industry, these roles are often labour-intensive, unregulated and involve long hours (Makone et al., 2017). Despite high rates of female employment, men have control over the financial proceeds in most tea farms. In the value chain for the production of fuelwood and other tree products, women face issues related to land and tree tenure, with lack of access to credit.

The Gender Empowerment Platform was developed by the Sustainable Trade Initiative (IDH), to address inclusion and other issues. KTDA is already part of this initiative, and it is recommended that whenever changes are planned to fuel supply modalities, it should actively engage with the Gender Empowerment Platform, as it offers a variety of support and guidance on strategies that can create best practice throughout the value chain for fuel production.

A specific gender and social inclusion framework should be developed for use of fuelwood and other biomass fuels, which sets out targets and review processes for the producers, suppliers and consumers. This should include contextual factors (economic, governance, sociocultural), whilst targeting different forms of inequalities. The improvement of women's safety through the value chain should have due prominence.

A landscape approach should be considered by any company considering expanding its range of fuels, to help develop policies and practices for G&I and other issues such as ecological protection and local community engagement. The Initiative for Sustainable Landscapes is an example, which worked to promote healthy forests (and social issues therein) in Kenya's Mau Forest, helping to improve social standards in agroforestry.

In-depth assessments should be made for any current and expanding engagement with farmers, plantation owners or briquette manufacturers. Tea factories should seek to promote equal opportunities when engaging with smallholder farmers for fuel sourcing, and facilitate an assessment of household dynamics, labour dynamics and financial control. Whether this is helping women access finance, or engaging a larger number of female-run farms in fuel supply, an understanding of the intricate dynamics should be sought, so as to create targeted approaches when trying to increase not just female engagement, but also helping to ensure that the benefits are more widely shared.

5.6 Institutional, market and regulatory framework

The privatisation of KTDA from a government parastatal to a limited company in 2002 began with Government Sessional Paper No. 2 on the Liberalisation and Restructuring of the Tea Industry (Ministry of Agriculture, 1999), which set out the problems with parastatal status and recommended a series of changes that would transform KTDA to a private company. This company would eventually have over 650,000 smallholder farmer shareholders owning majority shares in 54 KTDA tea companies, comprised of 70 factories. With this transformation, a new dynamic was created in the institutional, market and regulatory framework for Kenya's tea sector. KTDA operates in a highly structured bottom-up framework, in which decisions on investment, management, operations and fuel choices start at a factory level.

Alternative energy initiatives may be catalysed by KTDA MS in Nairobi, to demonstrate the viability of fuels that can diversify factories' fuel sources and make them more resilient to policy, regulatory, market and climate changes. This framework has strengthened KTDA and its shareholder factories and companies to operate successfully in a rapidly changing economic, financial and environmental world. KTDA may also operate tenders to identify costed and performance-checked fuels. But it is ultimately the decision of individual factory boards, managers and shareholders as to which fuels and technologies they adopt, based on their own situations, preferences and financial positions.

These decisions are not made in isolation. They reflect the economic realities of the day, which are in turn often the result of Government policy towards different energy options. It is known, for example, that fuelwood from large-scale commercial suppliers (such as Kakuzi) is subject to 14% VAT. Until 30 June 2021, biomass briquettes were subject to the same VAT. Parliament has now exempted biomass 'sustainable fuel briquettes for household and commercial use' from VAT under the new Finance Act (Republic of Kenya, 2021). This is an important step, given that costs can rarely be offset by producers against inputs, so are passed directly on to customers. Fuelwood being transported in bulk is also subject to movement permits issue by KFS and – if it crosses County boundaries - additional cess payments to County governments.

Fuelwood grown on small private farms by individual households and moved using local means is not subject to such regulation or cost– or at least none is routinely imposed. This arguably creates a playing field that is not level, when comparing the operations of commercial forestry concerns – including KTDA's own fuelwood plantation investments – and briquette manufacturers, against the largely unregulated operation of small-scale individual wood suppliers and providers.

In order to make the relative costs of each fuel option comparable, and to open up fairer competition, it would be appropriate for VAT to also be waived on commercial plantation-based fuelwood as it now is on briquettes. Levelling the playing field for commercial fuel growers and briquette producers in this way is important to facilitate fair competition with informal, generally smallholder, wood producers. The alternative, which would be higher taxation on smallholder producers, would likely be impractical and cost-ineffective.

Given the high population pressure on Kenya's highest potential land, and the competing demands for food, fuel, cash crops and settlement, there is also a need to maximise biomass productivity from farm plots and commercial tree plantations. Organisations such as KEFRI, Gatsby and Komaza have been supporting small-scale forestry investors with access to better tree germplasm and technical advice. Such programmes should be reinforced and expanded, to increase the fuelwood yields from planted trees, to improve returns to farmers and to generate more sustainable suppliers for commercial users such as the tea industry.

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 nine 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 tea processing sectors, where applicable, but not to quantify either total energy demand in the sector, or the potential scale of the replication opportunity.

Over the past 50 years, tea has become one of the most important cash crops and foreign exchange earners in Eastern, Central and Southern Africa. While Kenya leads Africa in the production and export of tea, other BSEAA target countries, namely Ethiopia, Uganda, Rwanda, Tanzania, Mozambique, Zambia and South Africa have made serious attempts, mostly successful, to use tea as a key driver to rural, social, economic and export development over the past five decades. In all these countries, with the exception of Kenya, plantation-grown trees, supplemented by purchases primarily by smallholders, have provided the bioenergy to fuel the boilers to process the tea. The following summarises how this has progressed over the past five decades after independence.

5.7.2 Country tea sector profiles

Eight of the ten BSEAA2 target countries produce tea, with the vast majority producing black tea. Kenya ranks highest in African tea production and exports. African teas rank the highest in terms of international prices paid owing to their strong quality and propensity for blending with other, less strong, black teas. Every country listed in Table 5.3 below exports most of its tea, with the exception of Ethiopia, which uses domestically produced teas to reduce imports.

Table 5.3: BSEAA2 target country tea production, 2019 (tonnes)

Rank	Country	Tea production (t/yr)
1	Kenya	458,850
2	Uganda	73,486
3	Tanzania	36,854
4	Mozambique	32,921
5	Rwanda	31,068
6	Ethiopia	10,388
7	South Africa	1,469
8	Zambia	953

Sources: (Kenya Tea Directorate, 2021), (FAO, 2019)

Ethiopia: Tea production in Ethiopia began during the late-1920s, with the establishment of the Gumaro estate by the Empress Zewditu in Iluababora zone of Oromia region in the southwest. Gumaro has about 1,000 ha of eucalyptus trees which provide the necessary fuel for tea processing. Ethiopia's second tea estate was established at Wush Wush as a trial in 1973 and expanded by the government in 1981 to 1,249 hectares. As with Gumaro, Wush Wush has about 1,000 ha of eucalyptus planted for all its heat needs. Both factories are owned by Ethio AgriCEFT (EATTA, 2021). Total annual production of the two tea estates ranges from 5,700 – 7,000 t (New Business Ethiopia, 2020) from approximately 2,000 ha of tea (Hall, 2000). The Ethiopian Coffee and Tea Authority under the Ministry of Agriculture was re-established in 2016. Far more finance, technical assistance and attention is paid to coffee than to tea, as coffee is Ethiopia's largest export crop. Most of Ethiopia's tea is auctioned through EATTA with Ethio AgriCEFT the only Ethiopian member among EATAA's 220 members (EATTA, 2021).

Mozambique: Mozambique was a large tea producer during the 1930s and 1940s, with production centred on Zambezia Province and the town of Gurúè (Hall, 2000). The districts of Gurúè, Milange, Tacuane and Socone are the key tea production centres. 18 tea companies survived the war for independence (which ended in 1974) and Mozambique was Africa's third largest tea producer until 1980, when the civil war led to a virtual cessation of production (Hall, ibid). Recovery has been slow since the war ended in 1992, and only five estates had been rehabilitated by mid-2020. However, Mozambique's tea sector has grown at a remarkable rate over the past 20 years, almost catching up with Tanzania. All tea is processed using purpose-grown eucalyptus which, in almost all cases, is grown in the factories' own plantations. The tea sector continues to grow rapidly. There are 39,000 ha of mostly old plantations, of which ~85% are under government ownership. There is currently no smallholder tea production. Mozambique, through several factories, is a member of the EATTA and uses the Mombasa Auction to sell most of its tea. EATTA has been instrumental in mobilising funds for developing micro-hydro facilities for the tea factories as part of its 'greening tea' initiative (IED, 2006). Fuelwood is the primary source of heat for process heat.

Rwanda: Tea is a major and rapidly growing industry in Rwanda which accounts for over 34% of the total value of exports. Rwanda has 26,000 ha of highland tea with annual production of ~30,000 t of mainly black tea. Tea is produced on eight government-owned plantations, three cooperatives and 11 smallholder associations, organised under the Rwanda Tea Authority (Rwanda Development Board, 2021). Virtually all thermal energy for tea processing in all Rwandan tea factories comes either from the factories' own eucalyptus plantations, or from out-sourced eucalyptus from other plantations and woodlots. The sector is highly productive and Rwandan teas command the highest prices of any of the target SSA countries with 97.3% of its made tea exported, mostly via the EATTA, of which the Rwanda Tea Authority is an active member. A number of international institutions, foundations and NGOs have worked since 1994 to support Rwanda smallholder tea (Ethical Tea Partnership, 2020).

The Gatsby Trust launched the Imbarutso Project in 2011 to bolster the sector's competitiveness and ensure that smallholders benefit from its growth. Gatsby's philanthropic investment vehicle, East African Tea Investments, in partnership with The Wood Foundation Africa, acquired majority shares in the Mulindi and Shagasha factories, with the intention to eventually fully transfer ownership of the factories to smallholders (Bourque, 2020). KTDA MS was contracted as managing agent for these two factories. Gatsby's experience with a similar smallholder programme in Tanzania (see below), working with the Wood Foundation Africa[25] and UK Aid in Nyaruguru North, Rwanda started in 2017, and was recognised by the Rwandan Government as the 'Top Foreign Direct Investment' in 2018. Working with 10,000 out-growers organised as the Rugabano Outgrowers Services Company, Unilever is developing an 800 ha core estate and a new factory in Nyaruguru which will be majority smallholder-supplied. Gatsby Foundation and FCDO are partner investors in this venture (Bourque, 2020).[26]

South Africa: South Africa is not part of the EATTA, and its annual production of black tea in 2019 was below 1,500 t (Table 5.3, above), down from over 10,000 t in 1950. South Africa was a significant tea producer in Africa from the mid-19th century until 1949, when the industry collapsed due to high costs of production and low world prices (Hall, 2000).

Tea estates shifted primarily to sugar and other cash crops during the next decade. However, the South African black tea industry was revived in 1964 with government support and financial backing through the Industrial Development Corporation (Khumalo & Adeyeye, 2015). However, availability of water was a limiting factor in Natal Province, where most of the tea was produced. South Africa's tea sector has experienced considerable swings in production and exports, mainly due to significant

[25] www.thewoodfoundation.org.uk/
[26] www.thewoodfoundation.org.uk/venture-philanthropy-in-africa/tea-greenfields/

variations in rainfall and major changes in production costs occasioned by a regulated labour market (ibid).

Unfavourable international tea prices, removal of tariffs and increased competition from other African countries (such as Kenya) have further added to the decline in South Africa's black tea production (Harney & Sons, 2021). Consequently, most of the country's tea estates have closed over the past two decades. However, while South Africa's black tea output is low, it produces two popular specialty teas, rooibos and honeybush, which are increasingly popular internationally (Khumalo & Adeyeye, 2015)

Tanzania: Tanzania has a well-developed tea sector with around 23,000 ha under tea cultivation, split approximately 50:50 between smallholders and large estates. However, productivity on tea estates is approximately double that of smallholders, with estates producing 24,500 t and smallholders 11,700 t in the 2014-15 growing season (FAO, 2016). Exports over the past five years have ranged between 5,000-8,000 t/yr of mainly black tea via the Mombasa auction (EATTA). All Tanzanian tea factories utilise wood, almost entirely from eucalyptus either purpose grown on their own estates, or bought in from other suppliers.

There are more than 30,000 smallholder tea growers with average holdings of around 0.3 ha. The Tanganyika Tea Growers Association (TTGA) was established in the 1940s by large-scale tea estates. After the disruptions of the 'Ujamaa' period of the 1970s and 1980s, the sector underwent a revival, and the TTGA merged with the Tanzania Tea Producers Organisation in 1988 to form the Tea Association of Tanzania.

19 tea factories are owned by large-scale farmers/companies (e.g. Unilever, Williamson, Rift Valley Corp) and four are owned collectively by smallholder farmers, located in seven districts in three main tea growing zones. All factories use fuelwood as their primary source of heat, with fuel substitution programmes supported by the same international NGOs active in Kenya (e.g. Rainforest Alliance, Ethical Tea Partnership, Gatsby). Gatsby, Unilever Tea Tanzania and The Wood Foundation Africa formed the Njombe Out-growers Services Company (NOSC, 2020) as a smallholder – large processor tea sector model, elements of which are also being tried in Rwanda. Unilever Tanzania has made its Njombe tea factory available for processing green leaf tea from smallholders. Today, The Wood Foundation Africa manages four smallholder tea greenfield sites in Rwanda and Tanzania, representing a Foreign Direct Investment value of more than USD 150m in rural areas with limited alternative economic activity (NOSC, 2020).

Uganda: After Kenya, Uganda has the largest tea sector in SSA. Between 1971 and 1986 almost all its 18 tea estates and smallholder factories ceased operations. In 1988, the Government of Uganda, supported by the EU, implemented the Smallholder Tea Rehabilitation Project. The programme was successful with Uganda exporting 10,971 t in 1994 compared to 500 t in 1980 (Kiwanuke, 2013).

Marketing was liberalised in the early 1990s and government-owned factories were privatised in 1994. This has stimulated significant production increases. Smallholder tea rehabilitation and development programmes have assisted smallholders to rehabilitate their tea stocks and factories prior to the sale of four smallholder factories to farmers in 1995. Various policy reforms have been undertaken, including the removal of the Uganda Tea Authority monopoly on exports, valuation of export proceeds at the market exchange rate, liberalisation of export marketing, and permission for foreign exchange retention accounts (Kiwanuke, 2013).

Tea factories are privately-owned by 17 companies and individuals (including four smallholder association companies who own five factories), all of whom export under their own brand names. Effectively all Ugandan tea factories utilise wood, primarily eucalyptus grown either on their estates or bought in from other producers. About 55% of tea in the country is produced in large estates and 45% by smallholders. Uganda exports about 70% of its tea via the Mombasa Auction/EATTA, sells 20% by direct exports and sells the 10% balance locally (Kiwanuke, 2013). The Uganda Tea Association is the umbrella body for 95% of tea farmers and processors.

Zambia: Zambia was a latecomer to tea production in East and Southern Africa. Five years after independence, tea was planted in 1969 as a government pilot in Kawambwa District in the northern highlands of Luapula Province. The Kawambwa Tea Plantation started with 300 ha of tea and was incorporated as a state-owned Company in 1975, with a tea processing factory commissioned in 1976 (Hall, 2000). After over 20 years' operation, it was privatized under the ownership and management of the Zambia Forest and Forest Industries Corporation (ZAFFICO) as ZAFFICO Tea Company Limited (ZAFFICO Tea Company, 2018). However, neither state ownership nor privatisation has succeeded in making the plantation and factory viable, and both are currently non-operational.

5.7.3 Potential for replication of Kenya's alternative bioenergy experience in the smallholder tea sector

Kenya's experience with promoting smallholder tea producers and providing a platform for their organisation and growth has good potential for replication in other tea-producing countries in SSA. Several international programmes have been supporting this approach in other East African countries, notably the UK's Gatsby Africa and The Wood Foundation in Tanzania and Rwanda. These efforts are focusing on supporting smallholder ownership and management, and do not include efforts to switch any factories over from fuelwood to alternative bioenergy sources, as being done in Kenya in both the smallholder (KTDA) and estate (KTGA) sectors.

Kenya currently offers limited evidence for demonstrating the potential for alternative (non-wood) bioenergy for tea processing. Beyond the opportunistic use of locally available biomass residues and occasional briquette purchases by a sub-set of factories, Kenya's smallholder-owned tea factories have shown limited interest in purchasing alternative biomass fuels such as briquettes, including from providers that have been quality-checked and approved by KTDA.

This seems to reflect a preference of factory managers and workers to use locally sourced fuelwood, due to familiarity with its handling and combustion, and the relatively high prices of briquettes on a comparable cost basis. As noted previously in section 3.3, KTDA factories have not found it viable to install their own combustion-based CHP systems, as it is more cost-effective to use the limited supplies of available biomass for dedicated thermal use. CHP would require boiler replacement, as tea processing requires low pressure steam (8-12 bar), whereas CHP requires high pressure steam (35-50 bar) to drive backpressure or extraction turbines (US Dept. of Energy, 2016). This limits the replicability potential of the Bioenergy Case in the other tea-producing countries targeted under BSEAA2.

6 SUMMARY AND CONCLUSIONS FOR REPLICATION

Based on the analysis of KTDA's experiences, 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 non-wood energy sources in smallholder tea processing 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).

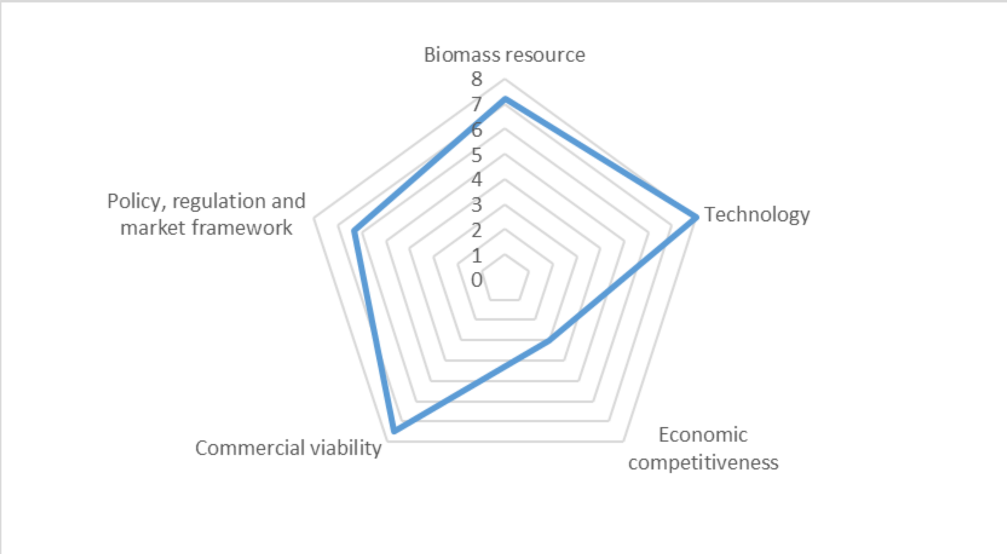


Figure 6-1: Impact of key factors on wider adoption of bioenergy case

Figure 6-1 shows that the availability and access to suitable biomass is not a bottleneck to wider adoption of non-wood biomass fuels. The biomass resource assessment have shown that the three residues already used for bulk briquette production, namely bagasse, sawdust and pineapple leaves are more than sufficient to meet KTDA's goal of achieving 20% non-wood bioenergy substitution. There is also sufficient production capacity available within KTDA's pre-qualified briquette suppliers - as well as a number of additional suppliers - to comfortably meet KTDA's potential requirement for alternative fuels.

Bagasse briquettes alone could supply energy for about 60% of Kenya's annual tea production of 439 kt. There is also substantial residue feedstock potential from a number of additional feedstock resources (e.g. maize stalks and cobs, wood processing residues and nutshells) which could be accessed for blending with these three primary feedstocks, though adoption potential is likely to be lower due to issues of cost, aggregation and suitability. In summary, , there are no significant supply-side barriers to increased briquette production, with sufficient feedstock to meet the demands of the tea sector and most briquette producers operating below capacity.

Based on the experiences of KTDA, Makomboki and briquette suppliers, technology selection, sourcing, operation and maintenance is not a constraint to the wider adoption of non-wood biomass fuels in this sector. Suitable steam boilers and ancillary equipment for the black tea industry are available from reputable local and international suppliers, and there is a sufficiently large customer base within Kenya to ensure reliable access to spares, replacements and manufacturer support. KTDA factories have many years of experience in operating this robust equipment and there is a well-developed operating expertise within factory staff and regional engineering support teams. KTDA Holdings Ltd.'s subsidiary company, TEMEC, can repair, maintain and even produce key technical equipment and spares for KTDA's factories.

Substitution of fuelwood with briquettes is not a technical obstacle and with training of factory personnel and machinery upgrades (such as the use of movable grates, to address clinkering and ash removal, and automatic briquette feeders), tea factories could achieve briquette feeding ratios greater than the 20% blending level targeted by KTDA. There are also dedicated boilers on the market that can operate with 100% briquettes, pellets or loose biomass residues. But for economic reasons discussed below, KTDA factories have not considered investing in full equipment replacements of this nature.

Economic analysis shows an unfavourable result for the partial substitution of fuelwood with briquettes, resulting in a higher cost of thermal energy. Increasing the percentage of substitution only increases this cost, since the cost of energy from briquettes is higher than that from fuelwood. Sensitivity analysis shows that the tipping point of viability is achieved at a briquette cost of around USD 75/t, which is substantially lower than the current cost of around USD 168/t. While there may be boiler performance improvements attributable to the use of drier and more standardised briquettes, this cost differential has meant that no more than three KTDA factories have so far bought briquettes from the three suppliers pre-qualified under the latest procurement round.

Although energy from briquettes is around twice as expensive as fuelwood, there are a number of commercial benefits that might motivate tea factories to consider using briquettes to supplement fuelwood. Such motivating factors may include market expectations, the need to ensure that fuel supply is diverse, secure and stable, and the part that such innovations can play in building functional relationships with supportive development partners. However, these benefits are currently insufficient to overcome the cost barrier. Despite the presence of ample feedstock and sufficient production capacity amongst pre-qualified briquette suppliers, there has therefore been only limited uptake of briquettes across the KTDA factory network. Unless there is a significant change in relative fuel costs, this suggests very limited replication potential within KTDA factories, who can access sustainably produced fuelwood from local farmers (often their own shareholders), KTDA plantations and other suppliers, at lower cost.

The institutional, market and regulatory assessment indicates that KTDA operates in a highly structured, bottom-up framework, in which decisions on investment, management, operations and fuel acquisition start at a factory level. Alternative energy initiatives may be promoted by KTDA Management Services, but it is the decision of individual factories, and ultimately their farmer members, to decide which fuels and technologies they adopt, based on their own situations, preferences and financial positions. Fuelwood grown on small private farms is currently the cheapest option, as it is not subject to regulation and costs incurred by plantation-grown wood and biomass briquettes, such as VAT, movement permits and county cess payments. In order to reduce the relative costs between these fuel options, a VAT exemption awarded to briquettes in July 2021 was one such step in this direction. Exemptions from other permits and fees would improve the prospects for commercial forestry concerns and briquette manufacturers to compete with informal wood producers.

Kenya's promotion of smallholder tea production, ownership and management has good potential for replication in other tea-producing countries in SSA. Several international organisations (such as Gatsby and The Wood Foundation) are already supporting this approach elsewhere in East Africa. However, the Kenya experience suggests there may be limited potential for alternative bioenergy for tea processing in other BSEAA2 target countries. As in Kenya, fuelwood is the key fuel in almost all tea factories in SSA, whether large tea estates or smallholder cooperatives. There is no evidence of commercial motivation for purchasing alternative fuels, beyond the opportunistic use of locally available biomass residues. Given the currently weak economic case for part substitution of fuelwood with biomass briquettes, this limits the replicability potential of the Bioenergy Case in the other tea-producing countries targeted under BSEAA2.

In sum, KTDA's experience of exploring alternative fuel options for its factories has been valuable as part of a wider rationalisation of energy consumption within the smallholder tea sector. This has revealed the scope for numerous improvements in the way fuel is handled, prepared and fed, and the ways in which boilers and related machinery are operated, managed and maintained. So while an envisaged switch away from fuelwood to alternative forms of bioenergy is assessed to be more expensive in the tea sector and currently suggests limited replication potential, a potential does exist for strengthening the business case for such enterprises through more equitable regulatory and fiscal treatment of biomass briquettes and sustainably grown fuelwood. This will ultimately also support the diversification and strengthening of bioenergy supply chains on which tea factories depend, even when retaining a fuelwood-dominated supply system.

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Appendix 2: People consulted

Organisation	Name	Position	Mode of Contact
Ikea Foundation	Jeffrey Prins	Head of Portfolio	In Person
Global Supply Solutions	Allan Marega	Founder and CEO	In Person
Kakuzi	Wilson Odiyo	Assistant General Manager, Corporate Affairs	In Person
	Sammy Chege	Senior Estate Manager	In Person
	Francis Wafula	Field Manager	In Person
Kings Biofuels	Festes Ngugi	CEO	In Person
KTDA Management Services	Alfred Njagi	Managing Director	Call
	George Odhiambo Oselu	Forest Manager	Call
	Hilary Ronoh	Energy Manager	Call
	John Langat	Development Engineer	Call
	John Mwenda	Maintenance Manager	Call
	Julius Onguso	Fuelwood Manager	Call
	G Godana	GM, Operations	Call
	Elijah Karoki	Regional Engineer (Region 1)	In Person
	Erick Mwangi	Regional Operations Manager (Region 1)	In Person
KTDA Makomboki Tea Factory	Zephania Miano	Factory Manager	In Person
Lean Energy Solutions	Vijay Shah	Production Manager	In Person
	Brenda Omollo	Production Assistant	In Person
Tamuwa	Nils Razmilovic	Co-founder	Call
	Nilesh Patel	Co-founder	Call
	Sylvanus Onyango	Production Manager	In Person

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, biomass resource availability and bioenergy potential are summarised in the tables below.

Biomass resource assessment table

Crop	Feedstock	Production of crop (t)[1]	Area of crop (ha)	Total biomass (t)	Recoverable fraction	Biomass potential (t wet basis)	MC as received (wt%)[2, 3, 4, 5, 6, 7, 8, 9]	Biomass potential (t d.b.)	HHV (MJ/kg)[2, 3, 4, 5, 6, 7, 8, 9]	Bioenergy potential (GJ)
Sugarcane	Bagasse	5,262,157	73,065	1,578,647	0.4	631,459	45	347,302	17	5,904,140
Maize	Stalks & cobs	4,013,777	2,141,743	2,809,644	0.3	842,893	30	590,025	17	10,030,429
Cassava	Stalks	946,076	61,592	473,038	0.6	283,823	70	85,147	18	1,532,643
Roundwood	Wood processing residues	505,200	-	227,340	0.6	136,404	30	95,483	19	1,814,173
Pineapples	Leaves	349,431	9,757	87,358	0.8	69,886	9	63,596	19	1,195,613
Sawnwood	Sawdust	177,600	-	66,600	0.6	39,960	30	27,972	19	531,468
Coconut	Husk	92,560	82,921	32,396	0.6	19,438	15	16,522	21	338,700
Rice	Husk	110,325	25,966	22,065	0.6	13,239	10	11,915	19	226,387
Macadamia nuts	Nutshells	26,773	4,231	19,544	0.6	11,727	10	10,554	21	221,632
Cashew nuts	Nut shells	11,677	22,655	7,940	0.6	4,764	11	4,250	21	87,118

Biomass resource assessment table (continued)

Crop	Feedstock	Production scale	Current use	Existing supply chain?	Mobilisation
Sugarcane	Bagasse	Small & large scale	Used by sugar mills for processing energy; competition with other users	yes	Easy to mobilise where available from sugar mills.
Maize	Stalks & cobs	Small scale individual	Used as animal fodder; return to field as fertiliser/nutrient/organic matter; unused residues left on field or disposed to land	no	Very scattered, mainly available on small scale lacking infrastructure and resources for collection and transport. Seasonal availability further limits mobilisation. Potentially more feasible for use at household/community level.
Cassava	Stalks	Small scale individual	Stalks used as cuttings for new planting; stalks are also used as fuelwood in domestic setting; leaves are also used for food; unused stems and leaves left on field or disposed to land	no	Very scattered, mainly available on small scale lacking infrastructure and resources for collection and transport. The way of harvesting/season can further limit availability. Potentially more feasible for use at household/community level.
Roundwood	Wood processing residues	Small & large scale	Used during wood processing (kiln drying); used by other industries and commercial sector for processing energy; unused residues disposed to land or burned	yes	Mobilisation depends on scale of wood processing facility and demand from other sectors
Pineapple	Leaves	Small & large scale	Unused residue on field and processing sites	partial	Mobilisation depends on scale and location. Left on field scattered with limited infrastructure. Centrally available in processing facilities.
Sawnwood	Sawdust	Small & large	Used during wood processing (kiln drying); used	yes	Mobilisation depends on scale of wood processing

Crop	Feedstock	Production scale	Current use	Existing supply chain?	Mobilisation
		scale	by other industries and commercial sector for processing energy; unused residues disposed to land or burned		facility and demand from other sectors
Coconut	Husk	Small scale (dominant) & large scale	Used for mulching of palms; energy (heat on domestic level); small-scale commercial sector for heat generation; to produce coir; unused residues disposed to land or burned	yes	Mainly small/local scale processing, which limits mobilising husk; in the case of commercial processing of coconuts, husk can be collected in bulk from processing facilities
Rice	Husk	Small scale individual	Used as fuel for rice drying in mills; unused husk disposed or burned; increasingly used by other industries for energy generation, which means knowledge and experience, but also competition exists	yes	In the case of small-scale processing, scattered availability and infrastructure and resources for collection and transport can be limited. More feasible if large-scale commercial processing when easy to collect or used on-site
Macadamia	Nut shells	Small scale (dominant) & large scale	Used for heat generation in commercial sector at various scale; used at domestic level	yes	Mobilisation depends on scale of processing facility, availability and infrastructure and resources for collection and transport and demand from other sectors
Cashew	Nut shells	Small & large scale	Used for heat generation in commercial sector at various scale; used at domestic level	yes	

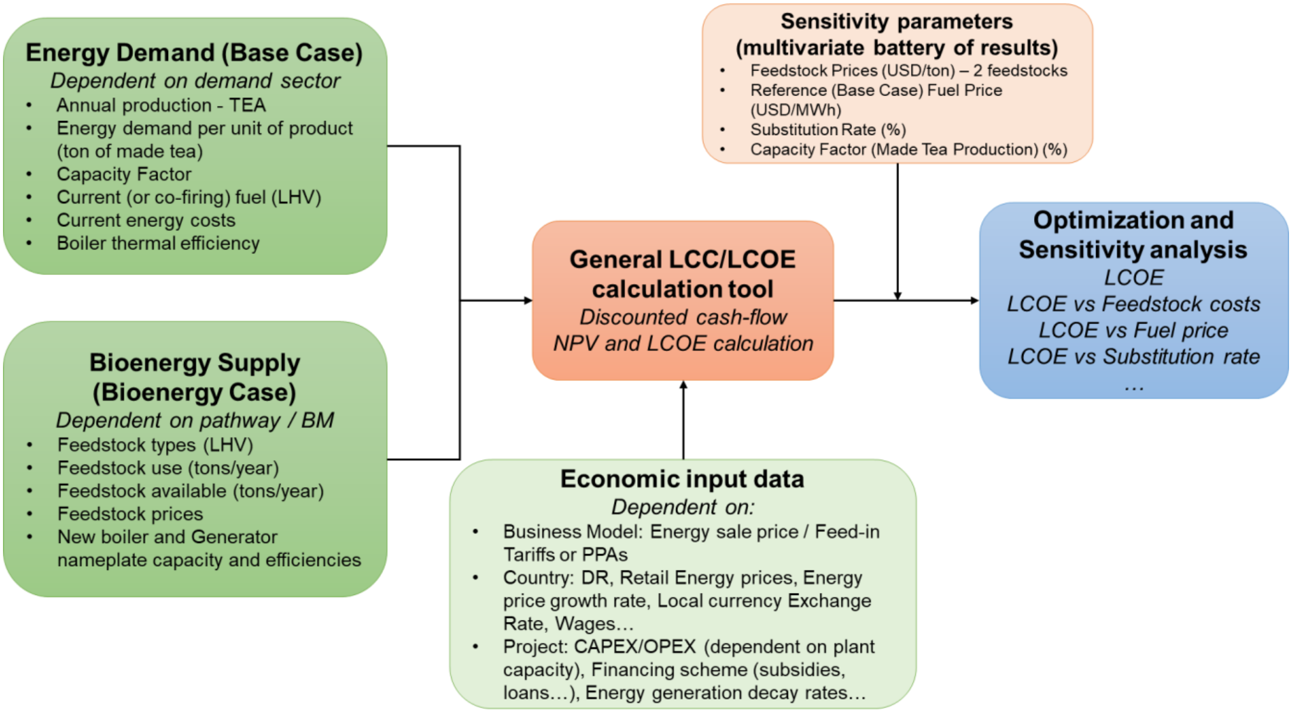
Residue-to-product ratios (RPR)

Feedstock	Residue type	RPR	Note
Sugarcane	Bagasse	0.3	30% bagasse from fresh cane [10]
Maize	Stalks& cobs	0.7	Ratio maize grain to residues ~1:0.7 [10, 11]
Cassava	Stalks	0.5	about 50% of root weight (wet) [12]
Roundwood	Wood processing residues	0.45	~40% of logs are sawn wood, 30% chips, 15% offcuts, 15% sawdust [13]
Pineapples	Leaves	0.25	20-25% of harvested fruit [14]
Sawnwood	Sawdust	0.15	~40% of logs are sawn wood, 30% chips, 15% offcuts, 15% sawdust [13]
Coconut	Husk	0.35	35% of coconut is husk [10]
Rice	Husk	0.2	0.2 kg husk per kg milled rice [7]
Macadamia nuts	Nutshells	0.7	0.73 kg shells per kg nuts [10]
Cashew nuts	Nut shells	0.7	0.7 kg shells per 1 kg nuts [8]

[1] (FAO, 2021) ; [2] (TNO, 2021); [3] (Ekop et al., 2019); [4] (Tsamba et al., 2006); [5] (Mansor et al., 2018); [6] (Xavier et al., 2016); [7] (IRRI, 2020); [8] (Uamusse et al., 2014); [9] (Forest Research, 2021); [10] (EED Advisory, 2018); [11] (Dafrallah et al., 2010); [12] (Zhu et al., 2015); [13] (Aebiom,2012); [14] (JRC, 2015).

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:

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

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

Appendix 6: Photos of Makomboki Tea Factory and fuel suppliers

Credit: All photos by Simon Thuo

Fuelwood stacked for sale, Kakuzi

Fuelwood delivery at Makomboki Tea Factory weighbridge

Fuelwood drying stacks, Makomboki

Fuelwood boiler (right) and decommissioned fuel oil boiler (left), Makomboki

Boiler feeding from handcart, Makomboki

Bagasse briquettes in storage, Makomboki

Bagasse prior to briquetting, Tamuwa, Kisumu

Dried pineapple leaf, Global Supply Solutions Thika

Blending sawdust and condemned maize for briquetting, Kings Biofuels, Murang’a

Kings Biofuels briquetting line

Global Supply Solutions briquetting plant, Thika

Bagasse briquette from White Coal, Kisumu (photo taken at Makomboki)