LIFE CYCLE ANALYSIS OF ALTERNATIVE BIOMASS ENERGY FOR COOKING: A CASE OF KITUI, KENYA AND MOSHI, TANZANIA

ABIGAEL AKOTH OKOKO

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DECLARATION

I declare that this thesis is my original work and has not been presented for a degree in any other university

ABIGAEL AKOTH OKOKO

C80/98010/2015

Signature: ……………………………….. Date: ……………

APPROVAL

This thesis has been submitted with our approval as the University Supervisors.

DR. SAMUEL OWUOR

Department of Geography and Environmental Studies,

University of Nairobi

Signature: ……….…………………….….……….. Date: ……………

DR. BONIFACE KITEME

CETRAD/ University of Nairobi

Signature: ……………….………..……………….. Date: ……………

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ABSTRACT

Wood-based biomass energy remains vital in meeting local energy needs for cooking in various parts of emerging countries, particularly in sub-Saharan Africa. This is largely because wood-based biomass energy can be obtained locally and is also affordable to the underprivileged population. Currently, concerns have been raised about the undesirable effects of reliance on wood-based energy. Continued use of wood-based energy sources has created pressure on natural resources leading to degradation of land, water and forests and emission of greenhouse gases. Additionally, there has been devastating effects on human health as a result of indoor air pollution. This has provided a platform from which the continued dependence of wood-based energy sources has been argued against. This calls for development of alternative biomass energy solutions that benefit local people without damaging the environment. It is imperative that their development is grounded on identification of suitable combinations of raw material and their conversion and consumption technologies. However, the effects of sustainable development of bioenergy processing are typically focused on industrialised countries. Nevertheless, improving awareness of impacts of bioenergy processing in emerging countries is imperative. Evaluating the sustainability of biomass energy supply chains is, however, often met with challenges, one of which is lack of data. In addition, the data is often fragmented or focus on only part of the whole life cycle. The objective of the study was to evaluate the performance of selected value chains for biomass energy used for cooking in Kitui, Kenya and Moshi, Tanzania. Their performance was based on their carbon footprints, life cycle costs and eco-efficiency. This study included firewood, charcoal, biogas, jatropha oil from hedges and crop residue briquettes for cooking at the household level while focussing on particular processing and consumption technologies of biomass energy in Kitui, Kenya and Moshi, Tanzania. Life cycle analysis as a methodological tool has been applied to offer useful evidence for the process of decision making process in these data scarce contexts. This study evaluated the carbon footprints of biomass of biomass energy by applying the Life Cycle Assessment. Their economic viability was evaluated using the Life Cycle Costing methodology. The study further determined the eco-efficiency of biomass energy pathways by integrating their carbon footprints and the life cycle costs.

The study used field data, databases (*Eco-invent*) and data from scientific literature to model the carbon footprint, life cycle costs and the eco-efficiency of these selected biomass value chains. The results indicate that the jatropha oil value chain holds the highest potential for carbon footprint reduction, as long as the jatropha plant is grown as hedges around the plots. Conversely, the jatropha oil value chain has the highest life cycle cost amongst the selected biomass energy value chains. Integration of the carbon footprints and the life cycle cost (eco-efficiency) of the biomass energy pathways indicate that viable options for biomass energy exist for households in Kitui and Moshi. The results presented can help stakeholders in decision making about substitute biomass energy value chains. Development and improvement of technologies used for biomass energy conversion and consumption provide significant opportunities for enhancing access to biomass energy for cooking. Additionally, they contribute to carbon footprint reduction strategies and provide a source of income especially for the rural and urban poor households.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study Problem

Energy is an essential resource that is required to satisfy basic needs that are relevant for human and social development. It is considered as a one of the most vital drivers of economic advancement and growth and social progress. However, Sub-Saharan Africa is characterised by poor access to modern energy which is among the leading development challenges facing the region (Tigabu, et al., 2015a). Since energy cuts across several sectors, its integration into socio-economic and environmental policies is of necessity (Colombo et al., 2013) so as to achieve many of the sustainable development goals. The provision of adequate, reliable and inexpensive energy is therefore of great importance (Kowsari & Zerriffi, 2011). However, according to UNDP (2013), the way energy is produced and consumed is of global concern since fossil fuels and greenhouse gas emissions trigger drastic changes in the climate and lead to environmental and social problems on every continent.

Understanding this human-energy-environment relationship has important implications for sustainable development decision making process. Other than the sustained economic use of the scarce resources, it is of importance to lay emphasis on identification of new energy technologies so as to cater for the increasing energy demands. Furthermore, these new technologies and energy sources need to be sustainable and easy to exploit with the potential to contribute towards achieving Sustainable Development Goal 7 which aims at ensuring access to affordable, reliable, sustainable and modern energy for all (UN, 2014). These interventions need also to contribute towards the effort aimed at tackling climate change and its impacts as envisaged by Goal 13 of taking urgent action to combat climate change and its impacts (UN, 2014). It is on this premise that biomass energy is expected to gain more emphasis in the coming years (World Bank, 2011a) and the reliance on it is likely to continue to a foreseeable future due to population increase, urbanisation (Felix & Gheewala, 2011; Njenga et al., 2013, Iiyama et al., 2014) and delay in providing access to modern sources of energy such as

Liquefied Petroleum Gas (LPG) and electricity. The attraction of biomass energy is premised on sustainable supply advantages, ease of its production, affordability and potential environmental benefits (Karekezi et al., 2004; Jingura et al., 2010; Felix & Gheewala, 2011; Clough, 2012).

Biomass energy is the largest source of energy globally. More than three billion people (nearly half of the world) are deprived of access to modern energy alternatives such as electricity and LPG (World Bank, 2011b). They therefore rely entirely on traditional biomass resources to meet their daily basic energy needs; one of which is cooking (Kowsari & Zerriffi, 2011; GEA, 2012). According to Bhattacharya (2002), energy needed for cooking often constitutes the largest share of the overall national energy use in developing countries. The total dependence on traditional biomass energy for cooking is associated with adverse environmental consequences (Guta, 2012) and health impacts accounting for over 1.6 million deaths annually (UNDP, 2010); majority of whom live in poor countries (Kowsari & Zerriffi, 2011; Guta, 2012). According to UNDP and WHO (2009), the emissions produced as a result of burning solid fuels in open fires and other traditional stoves (such as the three-stones fire place), contribute to substantial global warming effects largely as a result of partial burning of fuel carbon. This is an indication that the discourse on climate change and its impacts needs to factor in household energy.

According to Bailis et al. (2007), about 94% of the people living in the rural areas in Africa and 73% of those in the urban areas use wood fuels as their main source of energy. However, reports by Ndegwa et al. (2011) and International Energy Agency (2014), indicate that the urban settlements rely heavily on charcoal with rural households being more dependent on firewood. Wood fuels provide energy for heating and cooking within the households but also support small and medium industries like brewing, tobacco curing and brick making. The central role of biomass energy in energy provision is predicted to remain dominant in the coming decades especially in Sub-Sahara Africa (Iiyama et al., 2014) where wood biomass provides energy for about 81% of all the households (World Bank, 2011a). According to World Bank (2011a), approximately 730 million tons of biomass are burned annually, resulting to more than one billion tons of carbon dioxide released into the atmosphere in developing countries.

Wood-based biomass is the primary source of energy for a large majority of people in East Africa ranging between 68% in Kenya and 90% in Uganda (Byakola et al., 2009) and Tanzania (Gmünder et al., 2014). According to GoK (2014), biomass energy provides 68% of Kenya's general energy requirement whereas petroleum accounts for about 22% and electricity 9% and coal at less than 1%. Dalberg (2013), notes that in Kenya, the market for LPG is underdeveloped. Only between 5% and 7% of households rely on LPG as the main fuel for cooking. Its diffusion is, however, greater in the urban areas where 21% of the households rely on LPG. By contrast, only 1% of the rural households use LPG as a main fuel. Firewood is the primary source of cooking energy for 88.2% of rural households and only 10.3% of the urban households. Charcoal is relied upon by 30.2% of urban households while only 7.2% depend on it in the rural areas (Clough, 2012).

The socio-economic status of households determines the type of cooking fuel used. For instance, energy sources higher in the ladder of the energy matrix are cleaner and costly. Households with higher income levels are thus likely to use them. By contrast, firewood is used by households with a lower income (Kenya National Bureau of Statistics (KNBS) and Society for International Development (SID), 2013). In Kitui, only 3.8% of households are connected to the national grid with the level of access in the rural part being negligible (below 1%). Majority of the households (89%), rely on firewood as their main fuel for cooking, while only 1% of the households use LPG, 2% use paraffin and 8% use charcoal (KNBS & SID, 2013). There is, therefore, the need to embrace renewable energy strategies in Kitui County so as to improve access to energy by households (County Government of Kitui, 2014).

According to Felix & Gheewala (2011), the main sources of energy in Tanzania include charcoal, firewood and dung, in addition to other traditional fuels. Their use is growing significantly as a result of the growing population. The biomass energy sector supports a wide range of activities in both rural and urban areas, therefore spurring growth and development in the commercial, institutional and industrial sectors (Camco

Clean Energy (Tanzania) Limited, 2014). A large population in Tanzania, estimated at more than 90% of the population, heavily rely on wood-based energy to satisfy their cooking needs (Sawe, 2009; Clough, 2012). In addition, wood-based biomass energy generates at least one billion dollars in revenue to the rural sector, therefore providing income and livelihoods to the rural people, transporters and urban traders (World Bank, 2009; Sander et al., 2013). Charcoal provides primary cooking energy for 66% and 5.2% of the urban and rural households, respectively (Clough, 2012).

1.2 Statement of the Research Problem

Access to modern sources of energy such as LPG and electricity is limited within the study sites. Only 17% and 3% of the population in Kenya and Tanzania, respectively, have access to modern fuels (UNDP and WHO, 2009). The main source of energy in Kitui is firewood and charcoal for the residents in the urban and rural areas. Similarly, in Moshi, wood-based biomass energy such as firewood and charcoal remain the main source of energy for both rural and urban populaces. Concern around biomass use, its effects on the local environment, health, economy and society has been on the international agenda for many years. In the past however, not much attention was given to the fact that developing countries were stealthily becoming major contributors to the global environmental degradation while trying to satisfy one of the basic human needs: the need for cooked food.

Currently, concerns have been raised about the undesirable effects; majorly ecological and socio-economic; of reliance on wood-based energy in Kenya and Tanzania. The constant use of wood-based energy sources has created stress on natural resources leading to land, water and forests degradation and greenhouse gas emissions. Additionally, there have been detrimental effects on human health as a result of indoor air pollution. This has provided a platform from which the continued dependence of wood-based energy sources has been argued against. As the population in Kenya and Tanzania continues to grow and the economy expands, the competing demands on the existing natural resources will keep rising. The demand for the various types of biomass energy will also continue to grow, increasing the dependencies between urban and surrounding rural populations. In addition, technologies used for the production and consumption of biomass fuels are majorly traditional and inefficient.

The current state of reliance on wood-based biomass energy is unsustainable and has been linked to adverse socio-economic and environmental outcomes. These adverse effects are associated with technologies that are wasteful of biomass energy and are therefore considered as underdeveloped and also known to have low efficiency levels (Chinh et al., 2013; Iiyama et al., 2014). According to Okello et al. (2013), biomass energy resources are being wasted by the widespread application of inefficient biomass energy technologies which therefore increase the rate of deforestation and other associated environmental effects. The continued reliance on biomass energy is, consequently, expected to exacerbate these negative environmental impacts, economic productivity and human health.

Despite the widespread opinion that technologies used for making and utilising biomass energy are backward, inefficient and can potentially to result in detrimental effects on health (Sovacool 2012; Iiyama et al., 2014), it is hypothesised that these biomass energy may be substituted with other feasible energy solutions that also help alleviate poverty through income generation and ensure sustainable management of natural resources if properly implemented (World Bank, 2011a; Colombo et al., 2013; Elbehri et al., 2013). Energy efficiency is a significant aspect and can be determined during the production, distribution and consumption phases along the value chains (Bauner et al., 2012). In light of the biomass energy sustainability debate, there is therefore the need for a paradigm shift in the method by which biomass energy is produced, distributed and used along the value chain.

It is thus crucial to evaluate the environmental and economic performance of existing and future biomass energy value chains in Kitui, Kenya and Moshi, Tanzania. This calls for adequate evaluation methods that help practitioners and policy makers address energy poverty and at the same time mitigate their adverse effects. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are such approaches that have been effectively applied largely in the industrialised world. In addition, the study applies the eco-efficiency approach which integrates the LCA and LCC results with the aim of developing a framework that can be used in biomass energy sustainability assessment. This study, therefore, focused on some biomass energy such as the wood-based (firewood and charcoal), and alternatives such as biogas (from cow dung), jatropha oil (from hedges), and crop residue briquettes while paying special attention to selected production and consumption technologies.

1.3 Research Questions

This study was guided by the following research questions:

1) What is the carbon footprint throughout the value chain of alternative biomass energy for cooking at the household level?

2) What is the life cycle cost throughout the value chain of alternative biomass energy for cooking at the household level?

3) What is the eco-efficiency of alternative biomass energy value chains for cooking at the household level?

1.4 Research Objectives

General Objective

To evaluate the performance of selected value chains for biomass energy used for cooking in Kitui, Kenya and Moshi, Tanzania.

Specific Research Objectives

The specific research objectives of the study are to:

1) Evaluate the carbon footprints throughout the value chain of alternative biomass energy for cooking at the household level;

2) Assess the life cycle costs throughout the value chain of alternative biomass energy for cooking at the household level; and

3) Assess the eco-efficiency of alternative biomass energy value chains for cooking at the household level.

1.5 Justification of the Study

The need to improve access to sustainable energy options especially for rural and urban poor in Kitui and Moshi necessitated this study. The reliance on traditional biomass energy paths has often been associated with devastating environmental and socio-economic outcomes. Kitui in Kenya and Moshi in Tanzania were selected because they are not close to the major cities, thus reducing the influence of megacities on biomass energy production and consumption. In addition, wood-based energy such as firewood and charcoal provide the primary sources of energy used for cooking by households in the two case study sites and thus contributes to the rapid depletion of forests and environmental degradation. As such, alternative biomass energy solutions could be one option to address energy poverty. Alternative biomass energy solutions could be considered sustainable as determined by their environmental, economic and social performance throughout the whole value chain.

However, in Eastern Africa few data and information are available about the performances of biomass energy value chains and adequate approaches to evaluate these value chains are lacking. In industrialised and BRIC nations (Brazil, Russia, India and China), projects evaluating the performance of energy technological options apply life cycle methods which include Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). This study, therefore, adopts LCA and LCC as useful evaluation tools. The purpose is to evaluate biomass energy sustainability and development interventions aimed at socio-economic benefits as well as reduce environmental impacts; carbon footprints; in the data scarce context of Eastern Africa. This is a key requirement when determining the best point of intervention(s) along the biomass energy value chain.

The application of the LCA and LCC concurrently provides information that can be utilised in making strategic decisions on biomass energy value chains that have the least environmental impact (herein carbon footprints), and at the same time incur the least cost for every unit of measurement. In other words, the combination of the LCA and LCC allows for determination of the eco-efficiency of energy value chains. This helps decision makers and other stakeholders detect and exploit potential ecological and economic improvements of biomass energy value chains. In addition to contributing to the decision making process, this study generates localised Life Cycle Inventory (LCI) data that complements the weak and fragmented body of knowledge on biomass energy value chains and fills existing knowledge gaps in this data scarce context and thus can be used by other future studies. In doing so, the study also contributes to capacity building.

1.6 Scope of the Study

This study was part of a wider project on “Knowledge support for sustainable renewable energy policies: The prospects of pro-poor biomass energy value chains in rural-urban contexts in East Africa”, (Project No. IZ01Z0_146875) carried out under the Swiss Programme for Research on Global Issues for Development (r4d programme) between 2013 and 2016. Generally, the main aim of the project was to evaluate the prospects of sustainable biomass energy value chains in urban and rural settings in East Africa. The aim being to contribute to the formulation and implementation of knowledge based energy policies that improve access to energy for cooking. The project was made up of three work packages: 1) Value chain perspective, which this thesis is part of; 2) Regional perspective; and 3) Integration. The study was conducted in Kitui in Kenya and Moshi in Tanzania.

Energy for cooking can be provided by a range of different fuels such as, firewood, charcoal, electricity, LPG, paraffin, cow dung, biogas and biofuels from organic material. However, this study only focused on biomass fuels and includes wood-based energy sources such as charcoal and firewood, in addition to other alternative sources such as biogas, jatropha oil and crop residue briquettes which are produced and used at the household level. Biomass fuels are hypothesised to be environmentally friendly, inexpensive, non-toxic and generally acceptable to the urban poor and rural households, which then informed their selection. The jatropha oil included in this study only considered jatropha seeds from Jatropha *Curcus* hedges so as to exclude competition of land with food crops. Charcoal and firewood are relied upon by many of households in Kitui and Moshi for cooking like in many parts of the developing countries. On the other hand, biogas, jatropha oil and crop residue briquettes are included in this study as potential alternative sources of biomass energy.

This study focussed on specific technologies mainly used for the production and use of biomass energy. These technologies were selected in a participatory workshop in both study sites in June 2014. The study adopts Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) as evaluation tools for biomass energy value chains. LCA and LCC are used to model the environmental impacts (herein carbon footprints) and economic viability focussing on the selected biomass energy value chains while considering rural and urban contexts within the study sites. These evaluation techniques as applied in this study are used to identify the opportunities and risks associated with the use of certain biomass energy value chains in order to inform policy makers and other stakeholders in the biomass energy sector.

1.7 Limitations of the Study

Life cycle methodologies have their limitations. Lack of appropriate data for LCA in developing countries continues to be an obstacle. This necessitated the use of data, such as emission profile, from similar geographical backgrounds and also the use of efficiency data of technologies with similarities due to limited studies on them. Not all key data could be gathered from the field survey e.g. data on technology efficiency or material composition. Therefore, the study used data from other scientific literature based on a comprehensive review and the *Ecoinvent* database version 3.1. In addition, LCA studies are reliant on some assumptions which affect the results of such studies. Uncertainties can thus still be high as many assumptions are used to fill the data gaps. The assumptions used in this study have therefore been reported in a transparent and explicit way. This study only considered environmental and economic aspects of biomass energy pathways. This becomes a limitation since the decision by households about switching fuels considers many more issues such as social and technical aspects. It is also important to acknowledge that there exists an extensive variety of environmental impact categories such as eco-toxicity, climate change impact, acidification, photochemical oxidation and eutrophication, among others. The environmental assessment in this study was not comprehensive since the focus was only on carbon foot printing as one aspect of environmental impacts due to the global attention directed towards reduction of greenhouse gas emissions from household cooking fuels.

Since the study analysed alternative biomass energy scenarios, it is worthwhile mentioning that some selected technologies may not have already been familiar to the residents of Kitui and Moshi. Unavailable technologies in the field included improved basic earth kiln, *sazawa* charcoal stove, plastic biogas digester, VACVINA (Vietnam Gardening Association) biogas digester, jatropha oil manual and diesel powered presses, briquette manual and diesel powered presses, and the briquette stove. Data used for modelling their respective value chains was, therefore, obtained from *Ecoinvent* database, reports and expert interviews. Lastly, the currency exchange rates vary with time and, therefore, exchange rates during the time of LCC analysis (between February and March 2016) were applied where currency conversion was necessary.

1.8 Operational Definitions and Concepts

Biomass: Organic material that can provide fuel and/or heat used for cooking. Biomass is defined as organic material that is renewable and that contains chemical energy which can be converted to fuel.

Biomass energy: Heat energy generated from biomass fuels.

Calorific value: Amount of energy per kilogram of fuel when it is burnt.

Biomass energy value chains: The chain of activities through which biomass resources are extracted and transformed into energy for use by consumers.

Alternative biomass energy value chains: Other value chains other than the current ones in place that have the potential to provide energy for cooking.

Environmental effects: Harmful results of human activities on the biophysical environment.

Economic viability: Cost benefits outweigh losses generated along biomass energy value chain.

Eco-efficiency: Is an index the combines the ecological effects and cost of a value chain (World Business Council for Sustainable Development, 2000).

Life Cycle: Interlinked stages of a product system which range from extraction of raw material to final disposal.

Life Cycle Assessment (LCA): Method used to measure the ecological impact of a product throughout its life cycle from the extraction of raw material to end of life (ISO, 2006a).

Life Cycle Costing (LCC): Evaluation of costs associated with a product throughout its entire life cycle (Ciroth & Franze, 2009)

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews scientific literature on biomass energy. The chapter gives a detailed overview of biomass energy sustainability, including an account of their environmental and socio-economic impacts. Comparative studies relating to biomass energy are also reviewed and presented in this chapter, in addition to the economic issues surrounding biomass energy use. Based on the reviewed literature, this chapter presents the knowledge gaps that informed this study. Finally, the theoretical and conceptual frameworks which form the basis upon which the study is anchored are presented.

2.2 Biomass Energy Sustainability

Access to cheap, reliable and sustainable energy is an important precondition to realising economic development and poverty alleviation as envisaged by goal 7 of the Sustainable Development Goals (UN, 2015). The household energy sector in Africa mainly depends much on biomass energy since access to modern energy is delayed. Meeting the demand for cooking energy in cheap and viable manner thus requires a combination of approaches. The solution lies in development of sources of energy that are renewable by promoting interventions such as forest cultivation for provision of energy, improving design and construction of stoves and kilns, and by further promoting the use of alternative fuels such as biogas (Afrane & Ntiamoah, 2012). In addition, Kituyi (2004) states that there is need for the household energy sector in African countries to focus on biomass energy technological developmnet and its disemination as strategies aimed towards the achievement of short and medium term development objectives.

The sustainability of biomass energy can only be achieved if stakeholders tackle its economic, environmental and social dimensions. Elbehri et al. (2013), states that for biomass energy value chains to be considered sustainable, emission reduction, economic efficiency and sustainable energy production have to be considered. In addition, the relationship between biomass production, social and cultural issues has to be factored in while assessing biomass energy sustainability (Fortuna et al., 2012). Furthermore, it is important to assess the techno-economics of the whole pathway of biomass energy by comparing different supply chain pathways, so that the supply pathway with the best performance can be identified (Batidzirai, 2013).

To ensure environmental sustainability, the use of biomass energy has to factor concerns such as greenhouse gas emissions, natural resource degradation (soil, water, air, and forests), and biodiversity (Elbehri et al., 2013). The release of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere has drawn the attention of many establishments both globally and locally. Sustainable Development Goal 13 stipulates the need for pressing action to fight and mitigate climate change and its devastating effects (UN, 2015). This goal requires the integration of climate change mitigation measures into national policies and strategies. Furthermore, it spells out the need for improving education in addition to awareness creation and building human and institutional capacity on mitigating climate change and its associated effects, and finally, to adaptation and impact reduction. It is, therefore, important that all stakeholders including governments and industries increasingly be on the continuous search for more efficient and cost-effective technologies that have the potential to also minimise greenhouse gas emissions. With these strategies in place, there is the potential for growth in the carbon dioxide trade due to the upsurge in the demand for carbon dioxide neutral technologies (IEA Bioenergy, 2005).

Biomass energy is being embraced in many parts of the industrialised world as a pillar of low carbon growth (Owen et al., 2013). Encouraging the adoption of biomass is thought to be one of the ways through which the society can achieve sustainability by lowering greenhouse gas emissions which ultimately provide human life with the desired friendly climate conditions (Openshaw, 2010; Elbehri et al., 2013) and lowering non-renewable energy consumption (Heller et al., 2004) as opposed to the continuous over reliance on the not only limited but also exhaustible fossil fuels. Modern bioenergy systems are thought to have significant potential to substitute fossil energy carriers with corresponding reduction in greenhouse gas, while also improving environmental and socio-economic services (Batidzirai, 2013).

2.2.1 Environmental and Socio-economic Impacts of Biomass Energy

Residential combustion of biomass energy is an important source of carbon monoxide, methane, dinitrogen oxide and black carbon emissions. Carbon dioxide emissions are dependent upon the method by which the biomass is harvested. According to Kahrl et al. (2009), significant reduction in the amount of greenhouse gas emisions could be realised by accelerating the transition from traditional to modern energy carriers and technologies, even if biomass replacements are great. According to Zah et al. (2007), it is possible that the production of biomass energy can be done in a way that is ecologically sound and is pegged on adequate selection of raw materials and production technologies. Biomass energy may not resolve the energy challenges. However, it is possible to realise 30% saving on greenhouse gas emissions from use of biomass energy compared with fossil fuels. This can be achieved if biomass energy is produced in an ecologically sound manner, while reducing consumption, and increasing energy efficiency. This will be determined by the biofuel and the production pathway.

Current inefficient technologies of biomass energy production and consumption has led to negative consequences due to incomplete combustion and intense collection of firewood, causing massive deforestation and environmental degradation, especially in highly populated areas, in addition to indoor air pollution (GVEP International, 2010; WHO, 2010; Guta, 2012; Iiyama et al., 2014). These undesirable ecological and socio-economic effects of the reliance on biomass energy are manifested in terms of increased deforestation rates, environmental health problems, and inefficiency in the conversion of wood to charcoal (GoK, 2014). In order to reduce the rate at which the environment is degraded, Okello et al. (2013) state that measures such as improving the efficiency of these technologies have a great potential to contribute significantly towards saving energy.

Firewood

The usage of firewood with rudimentary cooking appliances together with inappropriate cooking space is the leading source of indoor air pollution in East Africa, adversely affecting health (Clough, 2012). One of the major barriers to the attainment of various development goals is indoor air contamination coupled with inefficient energy practices within the households (Felix & Gheewala, 2011). These practices are leading causes of mortality from respiratory infections, cardiovascular, and immune and nervous systems with women and children suffering the most, and therefore, increasing the universal burden of illness (WHO, 2010; L'Orange et al., 2012). Burning of solid fuels on an open fire or rudimentary cooking apparatus indoors is inefficient and also produces smoke and other air pollutants such as particulate matter and poisonous gases such as carbon monoxide, formaldehyde nitrogen oxides, polyaromatic, butadiene, benzene, and hydrocarbons (WHO, 2010; Felix & Gheewala, 2011; L'Orange et al., 2012). World Bank (2011b) estimates that by the year 2030, over 4,000 deaths will occur prematurely daily as a result of indoor air contamination. It is, therefore, important that programs promoting the adoption of fuel efficient biomass energy stoves take this as a matter of priority.

In Northern India, a chemical analysis indicated that the concentrations of major ions of aerosols and gaseous pollutants were lowered by an average of 32% when using improved cook stove as compared to the traditional cook stove. The higher amount of fuel used, poorer burning efficiency and volatilisation amount of the solid fuel during combustion when the traditional cook stove is used leads to its higher concentration of emissions. In addition, the improved cook stove reduced firewood consumption by an average of 41%, maintained cleaner kitchens and reduced time for cooking (Singh, S, et al., 2014). A study done in Malawi by Malakini et al. (2014) on the efficiency of three different types of cook stoves namely the three stones fireplace, the rocket stove, and the '*chitetezo*', found out that the rocket stove used the least time to cook and consumed the least amount of equivalent dry wood compared to the other two. According to MacCarty et al. (2008), laboratory tests show that enhanced firewood burning cook stoves considerably reduce the greenhouse gas effect of a cooking activity.

Charcoal

Charcoal in Kenya and Tanzania is mainly produced using traditional earth-mound kilns. This kiln is characterised by very low wood to charcoal conversion efficiency ranging between 10 and 15% (GoK, 2013; Gmünder et al., 2014), which wastes most of the energetic value of fuelwood. Kammen & Lew (2005), note that the energy conversion of the charcoal production procedure is reliant on numerous elements. These elements include type of the kiln, amount of moisture, wood types, arrangement of the wood in the kiln, and the expertise of the producer. Adam (2009), states that during charcoal making by means of the earth mound kiln, the heat lost as a result of radiation and erratic fires lowers its efficiency ranking. He goes ahead to note that the emissions of earth mound charcoal kilns and the conversion of wood to charcoal leads to additional carbon dioxide and methane. Furthermore, making of charcoal using the traditional earth kiln seems to be an important source of methane which is 21 times more active and potent on the greenhouse gas effect compared to carbon dioxide. The promotion of a sustainable charcoal industry therefore calls for integration of its various components, which encompass enhanced kilns, upgraded cooking stoves, and viable supply in the framework of enabling strategies (Senelwa et al., 2005; Gmünder et al., 2014).

A fully grown healthy tree is estimated to sequester about 5.2kgCO_2eq/year during the process of photosynthesis (IPCC, 2000). Harvesting of these trees for the purposes of firewood and charcoal provision implies removing the stored carbon and releasing it back into the atmosphere at a level higher than the absorption level (Nzila et al., 2012). In Brazil, Bailis et al. (2013) did a comparison of the environmental effects of charcoal production using the hot-tail and the metal container kilns. The hot-tail kiln was the most commonly used charcoal technology in the country, while the metal container was still being developed. They found out that the latter was an improvement over the former in reduction of the emission of greenhouse gases. The metal kilns likewise reduced the potential of ozone depletion, but then again increased the acidification and eutrophication potential. However, the effects on photochemical oxidation were varied.

Another study by Gmünder et al. (2014) in Tanzania comparing traditional and improved charcoal production technologies indicates the wood saving potential of the improved systems to be 66% but can range up to 85% in the best case scenario. These savings can be achieved if efficient stoves are used (up to 57% improvement) and if more efficient kilns are in place (about 20% improvement). Additionally, greenhouse gas emissions could be significantly reduced by 63% to 84% by implementing efficiency measures. In addition, many efforts have aimed at developing alternative cook stoves to not only shrink fuel use but also realize better emission performance (Huboyo et al., 2103). Senelwa et al. (2005) indicate in a study done in Kenya that emissions vary significantly among different charcoal species and with stove designs and that the improved ceramic stove emitted more carbon monoxide than the traditional stove. However, they found that the stove type had no significant influence on nitrogen dioxide, hydrocarbons and carbon dioxide emissions.

Bailis et al. (2003) in their study in Kenya conclude that charcoal use carries the largest burden of greenhouse gas emissions. Improved cook stoves are nevertheless very important for reducing greenhouse gas emissions from wood-based biomass use as they efficiently use fuel and reduce air pollutants affecting human health, mainly of women and children. Venkataraman et al. (2010), state that in order to realize the collective goals of fuel efficiency, protection of our well-being, reduced effects on climate and reduction of open-air contamination, it is imperative to move in the direction of “high-combustion-efficiency” and “low-emissions advanced-combustion” appliances that will not result in any substantial pollution. According to MacCarty et al. (2008), laboratory tests show that enhanced cook stoves that burn wood better have the potential to considerably shrink the global warming effect of cooking. However, the modernisation of the way biomass energy is produced and used could not only substantially contribute to climate change mitigation but also economic development and poverty alleviation (Owen et al., 2013).

Biogas

Facilitating the adoption of renewable energy technologies such as anaerobic bio-digesters is among the preferred policy responses to reduce the reliance on direct combustion of unprocessed firewood, charcoal, crop residues and animal wastes for household energy source (Tigabu et al., 2015a). Anaerobic biogas digesters could potentially be used to treat the organic portion of refuse material and when used in a completely engineered structure, they provide pollution prevention, in addition to allowing for production of energy in the form of biogas, recovery of compost and nutrients (IEA Bioenergy, 2005). With the continued development of the technology, anaerobic breakdown is becoming a strategic technique for the reduction of waste matter, in addition to recovery of renewable fuel and other useful products. It considerably minimises greenhouse gas emissions, eradicates odours, yields sterile manure and liquid based fertiliser rich in nutrients and make the most out of recycling (IEA Bioenergy, 2005). Consequently, biogas digesters provide a cleaner cooking fuel, which is more flexible and of higher quality then charcoal and firewood (Garfí et al., 2012; Tigabu et al., 2015b) that has the advantage of decreasing indoor air contamination and occurrence of respiratory illnesses since its burning does not yield particulate matter (Garfí et al., 2012).

A study done in Nepal indicates that the installation of biogas plants saves 2 tonnes/year fuel wood for cooking and 3 tonnesCO_2eq/year per plant (Ashden Award, 2006). In the Peruvian Andes, Garfí et al. (2012) report that production of biogas provides approximately 60% of energy requirements for cooking, resulting in a considerable decline in firewood utilisation and emission of greenhouse gases. This is an indication of the ecological paybacks when biogas becomes a substitute for wood-based fuels such as firewood and charcoal (Nzila et al., 2012). A life cycle assessment study by Perez et al. (2014), report that the environmental impact of the construction phase of the plastic tubular is higher than that of the fixed dome digester. This is due to the relatively short lifespan of the plastic materials. However, in terms of their global warming potential, the study reports similar results for both biogas digesters. This is an indication that the total carbon dioxide emissions of building resources were comparable for both digesters. It is, however, meaningful to state that there is a possibility for the global warming potential to decrease during the digesters use phase. In Kenya, Nzila et al. (2012), compared global warming potential of three types of bio-digesters namely “floating drum”, “fixed dome” and the “tubular digester”. The tubular and the fixed dome biogas lifecycle provide enhanced ecological presentation as compared to that of the floating drum. The floating drum they note produces the least decline in global warming potential. In the Peruvian Andes, use of the plastic tubular digester results in an annual decline of 2.7 tonns of emissions per household (Garfí et al., 2012).

Biogas as a clean fuel used in rural China is reported to have reduced 45,598GgCO_2eq per year from 1991 to 2005 (Yu et al., 2008). The study estimates that the reduction of greenhouse gases was 73,158 GgCO_2eq as a result of the use of biogas digesters. The emission of greenhouse gases as a result of biogas burning was only 36,373GgCO_2eq, noting that energy replacement coupled with proper management of manure effectively reduced these emissions. Carbon dioxide compared to methane, is reported to account for most of the emissions resulting from biogas burning. The study adds that energy substitution played the major role in reducing the emissions. Their study predicted that the overall generation of biogas in China was expected to reach 15.6 billion m^3 in the year 2010 and a further 38.5 billion m^3 in the year 2020, resulting in a greenhouse gas emission reduction of 28,991 and 46,794.90 GgCO_2eq, respectively. In addition to greenhouse gas emission reduction, the production of biogas as an alternative source of energy saved Chinese farmers large amounts of coal, straw, firewood, and electricity for their income and a bit of natural gas, refined oil and LPG.

An LCA study of biogas done by Rahman (2011), in Bangladesh indicated the possibility to substitute 15 tonnes of wood by biogas use within a period of 10 years. He further reports that the global warming potential is approximately 22 tonnes CO_2 equivalents following combustion and that the burning of methane shrinks the global warming potential by 109 tonnes of CO_2eq. He concludes that the application of biogas produced by anaerobic decomposition reduces a substantial quantity of global warming unlike the traditional practices. Agrahari & Tiwari (2014), in their study compares the use of cow dung and kitchen waste as feedstock for biogas production. They report that waste from the kitchen is better for the production of biogas. This is attributed to the low amount of solid content of kitchen waste compared to that of cow dung and which, therefore, enhances the activity of microorganisms. The utilisation of kitchen waste, however, would be more useful in community set-ups.

Despite the environmental benefits of biogas as an energy source, Nyagabona & Olomi (2009), documented low uptake of the biogas technology in Tanzania. Acceptability of the biogas stoves could be enhanced by modifying them in order to meet the various needs and preferences of the households. Some of the recommendations suggested for increased uptake of the biogas technology include the introduction of bigger burners especially for institutions; introduction of at least two burners for households; the stove to be made using quality steel or aluminium material; a ring to be fixed around the stove since the cooking pots often slide out of the cooker when cooking; and the stove should be set on a higher stand to avoid bending while cooking.

In a study done by Lwiza et al. (2017) in Uganda, respondents alluded that using biogas technology would not be meaningful if it could not be used to prepare their staple foods. The respondents stated that the taste of the food prepared using firewood was different from that prepared using biogas. The study reiterated the importance of the size and design of the biogas cook stove that suits the size of the pots used for cooking. In addition, the uptake and adoption of biogas is subject to perceptions and preferences of households. The study reports that the studied improved wood fuel stove was preferred over the traditional and biogas stoves. Efforts to improve uptake of biogas technology should not focus only on increasing the number of installations, but also, on increasing their acceptability and usability. This strategy requires a holistic assessment of the resources, risks and preferences of the households. Long term use of biogas technology is also likely if the households' purposes for adoption are met. These include, realising substantial decline in the use of firewood in addition to decreasing the expenditure on fuel for lighting.

Jatropha oil

A number of technologies can be used to produce liquid, solid and gaseous energy carriers from jatropha and its by-products. These technologies comprise anaerobic breakdown, gasification, trans-esterification, pyrolysis and combustion (Jingura et al., 2010). The main reasons for enhanced use of biofuels such as jatropha oil include employment of the local people; energy security; enhanced smallholder income; and their potential to mitigate climate change. Jatropha oil can be extracted easily using basic technology and are claimed to be carbon neutral and fossil free (Rajagopal & Zilberman, 2007; Achten, 2010; Muys et al., 2014). This is despite the waning interest in biofuels following documentation of the risks that biofuels posed to global land use, food accessibility and global habitat loss (Abdul-Manan, 2017). On the contrary, Jatropha is thought to regulate and stop soil loss, in addition to sequestering carbon which, however, depends on the farming method and intensity (Achten, 2010).

Ecological impacts can be produced at all phases of biofuel feedstock extraction and processing, though practices associated with change of land-use and intensification seem to take a leading role. The production of first-generation biofuels from existing feedstocks leads to reduction of emission by between 20% and 60% compared to fossil fuels. This can be achieved only if systems that are considered to be of great efficiency are utilised and exclusion of carbon emissions from change in land-use (Wiebe et al., 2008). Biofuel plants have the potential to grow on marginal land and could escalate carbon stocks while offering great potential for mitigating greenhouse gases (Muys et al., 2014). This depends upon the efficient use of the by-products generated from the biofuel production method (Achten et al., 2008) in addition to restoring the local biodiversity (Achten, 2010).

The main cause of carbon dioxide emission of jatropha oil value chain as documented by Paz & Vissers (2011) in Mozambique is the crop farming phase attributed by the nitrogen in the fertilisers. Changes in carbon stock as a result of changes in land-use have a huge influence on saving of greenhouse gas of jatropha oil value chain. A positive impact occurs if the land with annual crops such as tobacco or savannah is transformed to jatropha land due to the build-up of carbon of jatropha as a permanent crop. A negative effect, on the other hand, is realised if established scrubland or forestland is transformed into jatropha land due to their great carbon stock levels. The removal of semi-natural forests according to Achten (2010), causes a hefty load on the original greenhouse gas saving which will take a considerable lifespan before it is repaid. Furthermore, use of intensive single crop of jatropha is stated to have adverse effects on native biodiversity. Additionally, the intensification of the agronomy phase, coupled with transesterification will raise the requirement for greenhouse gas of the production phase. Paz & Vissers (2011) in their study, report that biodiesel produced and used locally in Mozambique leads to 48% greenhouse gas emission saving. Biodiesel which is exported abroad to the United Kingdom has the potential to save 39% of the greenhouse gas emissions.

Feto (2011), in a study done in Ethiopia reports that jatropha oil production based on hedge cultivation has greater saving on the demand for energy and greenhouse gas emissions as compared to that based on large scale cultivation. Hedge cultivation additionally reduces the pressure on land and reduces its competition with food crops. According to Achten et al. (2009), small scale jatropha oil production has added benefits, and only poses minor threats on ecosystem functions, biodiversity, and water balance. These additional benefits include additional crop to farmers and therefore, farmers can expand their revenue sources. In addition, jatropha pruning from jatropha can yield woody by-products and waste. These by-products and wastes can be combusted, therefore, reducing burden on the few forests and remaining woodlots. Furthermore, when established on the borders as a hedge, jatropha can be used as a live fence, therefore, excluding animals that browse. The hedge is used for the purposes of environmental restoration or protection of crops grown for food, since it is inedible to livestock.

In Thailand Prueksakorn et al. (2010), compares the energy balance of perennial and annual plantation systems of jatropha plant. The study reports that the energy consumption of the agricultural phase records the highest energy consumption for plantation systems; 38% and 68% for perennial and annual plantation systems, respectively. In the annual plantation systems, the contribution of the agriculture phase is higher due to the much higher usage of fertilisers, in addition to use of herbicides and irrigation since the trees are cut every year.

Briquettes

Direct combustion of crop residue such as rice husks is the simplest method of generating heat energy, and is a common practice in the rural households in developing countries (Thao et al., 2011; FAO, 2014). Although burning of agricultural residue is extensively used through the world to prepare farmlands, control weeds and pests, and remove wastes after harvesting, it is an important source of greenhouse gas emissions (Kahrl et al., 2009). In China, instances involving burning of agricultural residues happens on a huge scale extending up to 20% of the overall crop residues burned.

Therefore, controlling the burning of these agricultural residues can be a key greenhouse gas alleviation approach. Other additionally co-benefits include decreasing local concentrations of particulate matter, sulphur dioxide, and dinitrogen oxide, in addition to other toxic air pollutants. According to Kahrl et al. (2009), discovering alternative uses of these residues that have economic viability would reduce their burning to a greater degree. Some of the different uses of crop residues comprise returning a larger portion of residues to the soil; increasing use of these residues for feedstuff; use of small-scale gasifiers to gasify residues for local gas use in order to compensate wasteful biomass combustion; transforming residues to liquefied biofuels to counterbalance use of petroleum; use of small-scale power plants to generate electricity by using residues as a direct feedstock or by first transforming it to a syngas; and lastly, through using coal to co-fire residue in coal-fired power plants.

In addition, these crop residues can be used for the production of solid biomass fuels such as briquettes, pellets and charcoal (FAO, 2014). Though these options are faced with economic, logistical and technical obstacles, it is acknowledged that overcoming them would be an achievement towards greenhouse gas emission reduction (Kahrl et al., 2009). Reduction in greenhouse gas emissions could potentially be attained directly by decreasing burning of residue and secondarily through restoration of soil carbon, counteracting greenhouse gas emissions resulting from feedstock production, and offsetting the use of fossil fuel. The main drawback of utilising crop residues is dealing with its huge volume, which can be overcome by compressing the residues into briquettes (Thao et al., 2011). The conversion of residues into solid biofuels entails thermo-chemical processing, which increases the energy density of the residue and makes them more suitable for final energy consumption (FAO, 2014). Briquettes are the most common type of densified biomass produced in developing countries, which are directly used as substitutes for firewood or alternatively for carbonizing to make briquetted charcoal briquettes (Bhattacharya, 2003). The main aim of producing briquettes is to supply inexpensive, good quality cooking fuel and also create employment and generate some income (Njenga et al., 2013).

A study done in Kenya by GVEP International (2010), shows that considerable attention is being drawn to adoption and use of briquettes by households and institutions. Briquettes are a potential substitute to current biomass energy use practices which are presently resulting to serious stress on forests. A feasibility study done in Sudan by Hood (2010), shows that with the identification of an appropriate, efficient stove for burning briquettes, firewood use in camps for the internally displaced persons would be replaced at a rate equivalent to about 1.6 times the weight of briquettes. According to Hood (2010), the energy density of rice husk briquette is greater than firewood and one kilogram of briquette is required to replace 1.63kg of firewood. Mustafa et al. (2104) report that the burning rate of briquettes produced from different biomass residues increase with increasing compression pressure, notwithstanding the diverse particle size variations. They state that at greater compression pressure, the burn rate becomes moderately stable for the briquettes from the different residues. Furthermore, the burn rate of briquettes made from sawdust and groundnut shell is greater than that made of rice husk.

In Vietnam, a study by Thao et al. (2011), records that the use of briquettes has the potential to mitigate emission of greenhouse gas emissions as a result of their higher calorific value, higher density and higher efficiency of the stove efficiency compared to open burning of rice rinds. The study reports that stopping of open burning leads to a reduction of dinitrogen oxide and methane, therefore overall reduction in greenhouse gas emissions. In addition, alleviation of greenhouse gas emission can be attained by using rice husks instead of fossil fuels. Rousset et al. (2011) in their LCA study of charcoal briquetting noted a positive balance of carbon dioxide equivalents in the briquette production, however, stating a negative global warming potential. This was because the carbon dioxide emissions during the process of making the briquette was completely off-set for by the ecological quality of the raw materials which were used; that is, charcoal made from eucalyptus plantations and starch derived from babacu fruits.

The net reduction in the greenhouse gas emission when charcoal produced using wood from *miombo* woodlands is substituted with charcoal briquettes made from saw mill wastes ranges between 42 and 84%, depending on the carbon neutrality of the substituted charcoal (Sjølie, 2012). These substitutes may substantially decrease emission of greenhouse gases from cement manufacturing and in households that dependent on charcoal. The results, therefore, show that substituting charcoal made from *miombo* woodlands and coal with charcoal made of sawmill remains has meaningful impacts on the rate of greenhouse gas emission both in industrial sector and households (Sjølie, 2012).

Comparative studies on the environmental impacts of different biomass energy

In India, Singh, P, et al. (2014), compare the life cycle ecological impact of using firewood, charcoal, crop remains, cow dung, electricity, coal, LPG, paraffin and biogas for cooking. The study reports that the indoor air pollution as a result of combusting cow dung is double that of crop remains and approximately five times greater than that of firewood combustion. Emission of black carbon by dung cake is 1.3 times larger than that of crop remains and 1.5 times larger than that of firewood. Burning of cow dung emits the largest amounts of hydrocarbons while agricultural residues emit the highest amounts of particulate matter (WEO, 2006). The ecological impacts of LPG are higher than that of biogas due to the fact that biogas is made from organic wastes that are locally accessible in addition to being fully renewable (Singh, P, et al., 2014). Despite the fact that both dung cake and biogas utilise cow dung as the raw material, the study reports that potential for global warming of dung cake is 14 times higher than that of biogas. In addition, biogas promotion on a large scale provides enormous potential for greenhouse gas mitigation and provides extra co-benefits such as replacing chemical fertilizers, local capacity development and employment creation. A comparative LCA study of biogas, charcoal and LPG done by Afrane & Ntiamoah (2011) in Ghana indicated that biogas production and use as a cooking fuel would bring about many environmental improvements. This would significantly be achieved if the biogas cook stoves were designed to be more efficient and properly managed. A study by Huboyo et al. (2103), comparing the efficiency of various cook stoves indicates that the Jatropha *Curcas* Seed (JSC) stove showed a higher efficiency and lower specific fuel consumption compared to the woodstove. The configuration of the JSC stove does not allow addition of fuel during cooking. It holds a lower volume of fuel than what would typically be needed for preparing a meal. Thus, improving the refuelling process is vital for enhancing its performance.

2.2.2 Economics of Biomass Energy

Elbehri et al. (2013) state that the three most important criteria that will ensure the economic sustainability of biomass fuels is achieved include profitability, efficiency and equity. They further state that one method of evaluating the economic feasibility of biomass energy is by the development of cost data associated with production. Their total economic effectiveness and, consequently, long-term feasibility rest on technological advancements with the potential of reducing cost and comparative price attractiveness of the other uses of feedstock (Elbehri et al., 2013). According to the IEA Bioenergy (2011), biomass energy must be as cheap as, or, cheaper than energy produced from competing energy sources.

Charcoal

Collection of biomass fuel for provision of cooking energy especially for rural households is often unpaid as it is considered free labour provided by women and children. However, the commercial biomass energy sector provides income for hundreds of thousands of persons. It provides large sums of money to local economies through taxes, revenues and individual earnings along the whole value chain (Ingmar & Kees, 2011). For instance, the economic potential for charcoal is enormous and is projected to employ 12 million people by the year 2030 with its market value exceeding US$ 12 billion in the sub- Sahara region. Kenya’s charcoal trade is estimated to be worth US$ 0.3 billion per year (World Bank, 2011a) and Tanzania’s entire charcoal sector is valued at US$ 650 million (World Bank, 2009; Sander et al., 2013).

Sepp (2008), however, observes that despite the enormous economic significance of the charcoal market, it is generally viewed negatively, operating informally as illegal business with unclear operating framework for stakeholders. According to Ndegwa et al. (2016), these conditions do not create an incentive for sustainable supply of charcoal due to the low margins received by the producers. The lack of surplus forces them to rely on rudimentary technologies and non-regulated land management practices: earth mound kilns; permit-less clear-cutting or selective logging practices based solely on agreements with the land owner (in the best case); and use of household-based labour, which has low opportunity cost as an agricultural off-season activity. Nevertheless, demand driven market for charcoal will continue to increase in the coming years. As already projected for Tanzania, this market in both rural and urban areas in a business as usual scenario will nearly double from a consumption of less than 2 million tons in the year 2012 to approximately 4 million tons annually in the year 2030 (Camco Clean Energy (Tanzania) Limited, 2014).

Biogas

In China and India, the success of small-scale biogas digesters in offering energy that is clean and fertilizers of high quality has been documented. Use of biogas digesters results in reducing the demand for commercial fertilizers, consequently, assisting in environmental protection and improvement of human health status (Chinh, 2005). The use of digester effluent by households as fertilizer leads to household saving on their annual income (Garfi et al., 2012). In as much as biogas has the potential to resolve a number of the energy and ecological challenges faced by the poor rural and urban people, and industrial estates, biogas is characterised by the typically high capital cost of biogas digesters (Chinh, 2005; Arther et al., 2011). As a result, households may not be capable of paying the full price of the digesters. A study by Perez et al. (2014) documents that the capital costs of the plastic tubular digester was 12% lower than that of the fixed dome digester. The capital cost of the fixed dome digester was thrice the cost of the tubular. The plastic tubular digester, however, requires replacement of the plastic material every 5 years resulting in additional costs (Nzila et al., 2012; Perez et al., 2014).

Based on an economic perspective, the “floating drum”, “fixed dome” and “tubular digesters” offer energy independence by the users with corresponding fossil energy substitution saving of between 42.18 and 44.79 $ Cents/m^3 of biogas. On the other hand, the capital cost ($ Cents) for every unit of biogas that is generated ranges between 1.8

and 3.8. The tubular digester, however, provides the greatest energy independence by replacement of fossil energy for every unit of investment. Seemingly, lowest labour cost for every cubic meter of biogas produced is reported for the tubular digester as compared to fixed dome digester which has the highest cost of labour for every unit of biogas produced. In general, the fixed dome digester exhibits the largest overall costs for every unit of biogas generated. When the capital and labour costs components are added together and deducted from the energy autonomy, the subsequent net energy autonomy for tubular digester, floating drum and fixed dome indicate that the return on investment of these biogas systems is substantial (Nzila et al., 2012).

Jatropha oil

The economic incentive for biofuels is due to the fact that they are a convenient, inexpensive and can be produced by households. Therefore, considering the effect of biofuels on the allocation of resources, cost of food and energy, adoption of technology and distribution of income is crucial at this very initial phase of development (Rajagopal & Zilberman, 2007). Jatropha production in monoculture or intercropping systems under smallholder conditions is not economically viable in Kenya. This is attributed to the low yields, high costs involved in jatropha oil production and no systematic market already developed in Kenya. This leads to extreme uncertainties over its economic viability for small holder farmers (Iiyama et al., 2008). However, significant investment on jatropha should not be encouraged, except when grown as a live fence which is the least intensive and least risky option. From an economic point of view, cultivation in live-fence hedges is the most feasible form of jatropha production system as reported by Feto (2011) in a study of Ethiopian sites. A study by Cynthia & Teong (2000), indicates that it is more economical to use jatropha oil compared to jatropha biodiesel, adding that it is economically viable when large scale production of jatropha oil is considered. Hedge cultivation is identified as having some economic potential due to its lower associated investment risk and opportunity costs. Cultivation of fuel crops for biodiesel on small-scale is normally more economical if the different by-products are used economically or put into commercial use (UN, 2007).

Biofuels require intensive use of inputs such as land, water, crops and fossil energy, yet they all have opportunity cost (Rajagopal & Zilberman, 2007; Tomomatsu & Swallow, 2007). Up to 80% of the cost of production of jatropha seeds are made up by the cost of manual harvesting (Elhaj & Lang, 2013). The cost of biofuel production is also greatly affected by the cost of feedstock; in this case the jatropha seeds (Tomomatsu & Swallow, 2007). Examination of jatropha's cost-effectiveness points out concerns surrounding the cultivation phase, during which a sizeable amount of the full costs are experienced (Soto et al., 2013). Improvements associated with demand for chemicals and fossil fuels and transportation are required during the processing and use phases. Jatropha farms ought to be established on marginal lands without replacing natural vegetation with large-scale plantations. The replacement of natural vegetation with large-scale jatropha farms in Ethiopia is the principal reason of higher financial costs (Feto, 2011). On the seed processing front, biofuels such as jatropha oil can only compete with other fuels if the plants function at adequate economies of scale. This can be achieved by guaranteeing a steady source of feedstock and a reliable market demand of biodiesel and its by-products (Shinoj et al. 2010).

The application of small-scale jatropha production for the purpose of local oil use enables farmers to diversify their income sources. In addition, small scale jatropha oil production decreases the threats related to largescale monoculture. According to Achten et al. (2009), farmers can independently control primary investment and regulate their start up risks. This system should ensure that it offers benefits to the implementing farmer. Jatropha farming, oil processing, and delivery of oil and its by-products should be less expensive in terms of resource use, such as labour, water or finances, compared to gathering of firewood, the purchase of paraffin or other conventional fuels. Under such circumstances, jatropha cultivation can, therefore, be added to farmers' present activities on lands inappropriate for extension of the present activities or natural protection, but, however, appropriate for jatropha. In remote areas characterised by dwindling firewood stocks, jatropha oil systems may provide ways by which the livelihoods of smallholder farmers may be enhanced. This can be achieved by way of energy independence since the oil can simply be extracted using basic technologies and used in stoves, lamps and simple generators (Muys et al., 2014).

Crop residue briquettes

Biomass needs to be pre-processed, before it can be stored, in an efficient manner, transported, or used in numerous ways presently intended for fossil fuels. Long distance transportation of untreated biomass makes biomass uneconomical due to its low energy density (Batidzirai, 2013). High costs compared to firewood and charcoal; problems with maintenance of the equipment; vague policy and regulatory structures; unreliability of feedstock supply; comparatively low calorific values; and high initial capital costs have been documented as the major obstacles of scaling up of briquette enterprises (Energy and Environment Partnership, 2013).

2.2.3 Integrated Approach to Biomass Energy

Viable development of energy systems is becoming progressively more vital for policy and decision makers globally and meeting the three sustainability aspects of energy systems: environmental, economic and social (Santoyo-Castelazo & Azapagic, 2014). According to Kowsari & Zerriffi (2011), integrated methods of evaluating household energy use are essential. This approach offers a more representative and all-inclusive understanding of energy usage than isolated disciplinary studies. These kinds of methods need to concurrently address the social and behavioural elements of energy use in addition to the economic and technological features of energy usage.

One such approach is the “eco-efficiency” assessment, which the World Business Council for Sustainable Development (WBCSD) (2000, p. 7), describes as “delivering of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing the ecological impacts and resource intensity throughout the life cycle to a level at least in line with the estimated earths carrying capacity”. The theory of “eco-efficiency” lies on its ability to integrate two of the three pillars of sustainable development: ecology and economics. However, the eco-efficiency does not incorporate social aspect (Ehrenfeld, 2005). According to Santoyo-Castelazo &

Azapagic (2014), there is no overall best scenario, as each option studied is better for some sustainability criteria but worse for others. A greater requirement for technologies with lasting sustainable repercussions in the bioenergy sector has been extensively recognised (Dutta & Raghavan, 2014).

2.3 Gaps in Knowledge

A systematic review done by Robledo-Abad et al. (2017) shows that awareness on sustainable development effects of bioenergy processing is typically focused on industrialised countries. Nevertheless, improving awareness of impacts of bioenergy processing in emerging countries is imperative. Assessing the sustainability of biomass energy supply chains is, however, often met with challenges, one of which is lack of data. Many emerging countries do not have current data (Felix, 2016) that can inform the process of decision making. For instance, current forest records which are a prerequisite for sustainable wood fuel production are often not available (Sepp & Mann, 2009). In addition, the data is often fragmented or focus on only part of the whole life cycle (Felix, 2016).

Life cycle analysis as a methodological tool can be applied to offer useful evidence for the process of decision making process even in these data scarce contexts. This study shows the usefulness of LCA as a tool for evaluating the carbon footprint of biomass energy value chains (ISO, 2006a). There are two main advantages of using LCA: (1) use of generic data enables identification of impact hotspots; and (2) LCA enables iterative data improvement, supporting effective and efficient development of biomass energy models based on enhancements to the most important data elements. In LCA, generic data may be used to fill data gaps, for example, in data-scarce contexts and where context-specific data are not available. Use of secondary data is based on averages within close geographical proximities. Further, continual review of the study model, its goals and assumptions provides a framework for improving the various data elements along the biomass energy lifecycle. These aspects are important in LCA since the analysis helps stakeholders and policymakers obtain a better understanding of the carbon footprint of biomass energy, including identification of trade-offs between different options and areas for improvement along the life cycle of biomass energy.

However, LCA as a methodology has its limitations. Not all key data can be gathered, such as measurements of input and output data and technology efficiency. Uncertainties can be high because many assumptions are used to fill data gaps. Thus, there is a need for transparency in reporting. There is also lack of context-specific data in the Global South, since virtually all the life cycle inventory background databases were developed in Europe and the United States. This makes it especially difficult to assess human labour, which in the Global North is often replaced by mechanized and automated processes. Finally, this study focused on carbon footprints only, which is a narrow view of the issue, since family choices about changing to other sources of energy include many more dynamics such as economic, social and technical aspects that LCA does not address.

Kituyi (2004), states the need to explore the potential for life cycle thinking, for instance, in charcoal production and use. This methodological approach can be extended to other biomass energy value chains in Kenya and Tanzania so as to explore their overall sustainability. They provide useful information that can be used by policy makers to influence biomass energy policies in Kenya, Tanzania and the entire region. Life cycle studies on biomass energy have, however, mainly concentrated on biofuels in developed countries. The few life cycle assessment studies that have been done in developing countries have largely focussed on wood-based fuels such as firewood and charcoal (Bhattacharya et al., 2002; Bailis et al., 2003; Bailis et al., 2013; Gmünder et al., 2014). It is, therefore, important that other potential biomass energy solutions are evaluated based on a value chain approach while considering their environmental and economic performance. Furthermore, the incorporation of the environmental and economic outcomes of these alternative biomass energy value chains is of importance if biomass energy sustainability is to be achieved.

It is imperative to also investigate the economic viability and environmental impacts (typically greenhouse gas emissions and energy balance, but also potential for ecosystem services) of different bioenergy value chains, so as to optimise the sustainable delivery of biomass (Afrane & Ntiamoah, 2011; Batidzirai, 2013). This helps in identifying and evaluating the risks and opportunities, in addition to costs and advantages, linked to each value chain, taking into account site specific contexts as biomass value chains are dependent on geographical, environmental and institutional factors (Batidzirai, 2013). Evaluation of the entire value chain is thus of great importance to ensure a deeper understanding of the various environmental and economic factors associated with biomass energy production and use. This calls for development of alternative biomass energy value chain grounded on identification of suitable combinations of raw material and conversion technologies (Batidzirai, 2013).

While there are studies indicating human health impacts (WHO, 2007; WHO, 2010; WHO & Climate and Clean Air Coalition, n.d.) and greenhouse gas emissions (Bhattacharya et al., 2002; Bailis et al., 2003; Afrane & Ntiamoah, 2011; Bailis et al., 2013; Gmünder et al., 2014) and costs of different energy solutions in the domain of cooking (Afrane & Ntiamoah, 2012), hardly any study that analyses them in an integrated framework was found i.e., in the framework of eco-efficiency. The development and application of such a framework in the context of sustainability is, therefore, timely.

2.4 Theoretical framework

2.4.1 Sustainable Development Theory

Brundtland (1987, para. 27), describes sustainable development as “development which meets the needs of the present without compromising the ability of the future generations to meet their own needs. It is a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are made consistent with future as well as present needs”. The Brundtland Commission Report of 1987 states that the model of sustainable development does indicate absolute limits but restrictions levied by the current state of technology on environmental resources and by the capacity of the planet to absorb the impacts of human activities. The report further states that technology can be managed and enhanced to chart the way for economic growth. Therefore, technologies and energy sources need to be sustainable and easy to exploit with the potential to contribute towards achieving Sustainable Development Goal 7 which aims at ensuring access to affordable, reliable, sustainable and modern energy for all (UN, 2014). Furthermore, discourses on biomass energy sustainability need also to focus on interventions aimed at tackling climate change and its impacts as envisaged by Goal 13 of taking urgent action to combat climate change and its impacts (UN, 2014).

Environmental sustainability of energy can be linked to the promotion of renewable energy sources and energy efficiency. On the other hand, the economic sustainability relates to policies aimed at reducing the dependence on traditional biomass energy but instead, provide access to modern energy (UN, 2014). Energy efficiency policies must, therefore, be in the front-line of national energy strategies for the achievement of sustainable development. There is great possibility for advancement in this way. Modern appliances can be remodelled to provide equal quantities of energy-services with only two-thirds or even one-half of the key energy inputs required to operate basic (primitive) equipment. Energy efficiency solutions are often economical. Therefore, a safe, ecologically sound, and economically feasible energy value chain that has the potential to sustain human development in the forthcoming years is evidently important.

2.4.2 Eco-efficiency Theory

Eco-efficiency according to the World Business Council for Sustainable Development (WBCSD) (2000), is attained through the delivery of products and services at reasonable costs that fulfils human requirements by increasing the quality of life and gradually decreasing the environmental effects of the use of resources during their complete life cycle at a rate in line with the projected carrying capability of the earth. Eco-efficiency is an important theory which can assist businesses, persons, states or other bodies become more viable. The concept of eco-efficiency encourages products/ services/processes to realise additional value from lesser inputs of raw material and energy coupled with decreased emission. Biomass energy developers, therefore, need to consider the ecological and economic viability of biomass energy concurrently so as to provide “low emission and low cost” biomass energy value chains. The application of this theory in the context of developing countries is important as it provides information about the sustainability of biomass energy. This information can be used for development of strategic policies on biomass energy in a bid to enhance access to adequate, reliable, affordable and sustainable energy for all.

2. 5 Conceptual Framework

Biomass energy utilisation lies upon exploitation of resources using different technologies along the value chain. Assessing these biomass energy value chains with special focus on selected production and consumption technologies is important. This ensures that exploitation of raw materials and the release of emissions and wastes do not compromise the overall environmental quality. At the same time, it ensures provision of biomass energy at affordable costs. Therefore, this study is concerned with biomass energy value chains and, as such, the focus is on: (a) environmental impacts; i.e. carbon footprints of biomass energy value chains; (b) life cycle cost of biomass energy value chains; and (c) the linkage between carbon footprints and life cycle costs of the biomass energy value chains thus their eco-efficiency. The conceptual framework (Figure 2.1) of the study displays these different components and the linkages between them. The arrows portray dynamic relationships and influences, not direct causalities.

In order to evaluate the ecological impact (carbon footprints) of biomass energy value chains the associated inputs (raw materials, energy) and output (emissions and wastes) have to be considered. The carbon footprint of biomass energy is, therefore, influenced by the raw material and energy input and its emission profile. In order to reduce the environmental impact of biomass energy, its raw material and energy input together with the emissions should be reduced. On the other hand, the life cycle cost of biomass energy is determined by labour cost, cost of acquisition, operation and maintenance of selected biomass energy technological options. However, so as to evaluate the benefits and trade-offs of the different biomass energy options in a more comprehensive way, it is crucial to integrate both aspects: the carbon footprints and the life cycle costs. The WBCSD (2000), frames such an indicator as the eco-efficiency of products and process. Eco-efficiency brings together environmental and economic aspects necessary for economic prosperity with more efficient use of resources and lower emissions. They further state that eco-efficiency is achieved through the provision of goods and services at competitive prices that satisfy human needs and progressively reduce the ecological impacts of the use of resources throughout their entire life cycle.

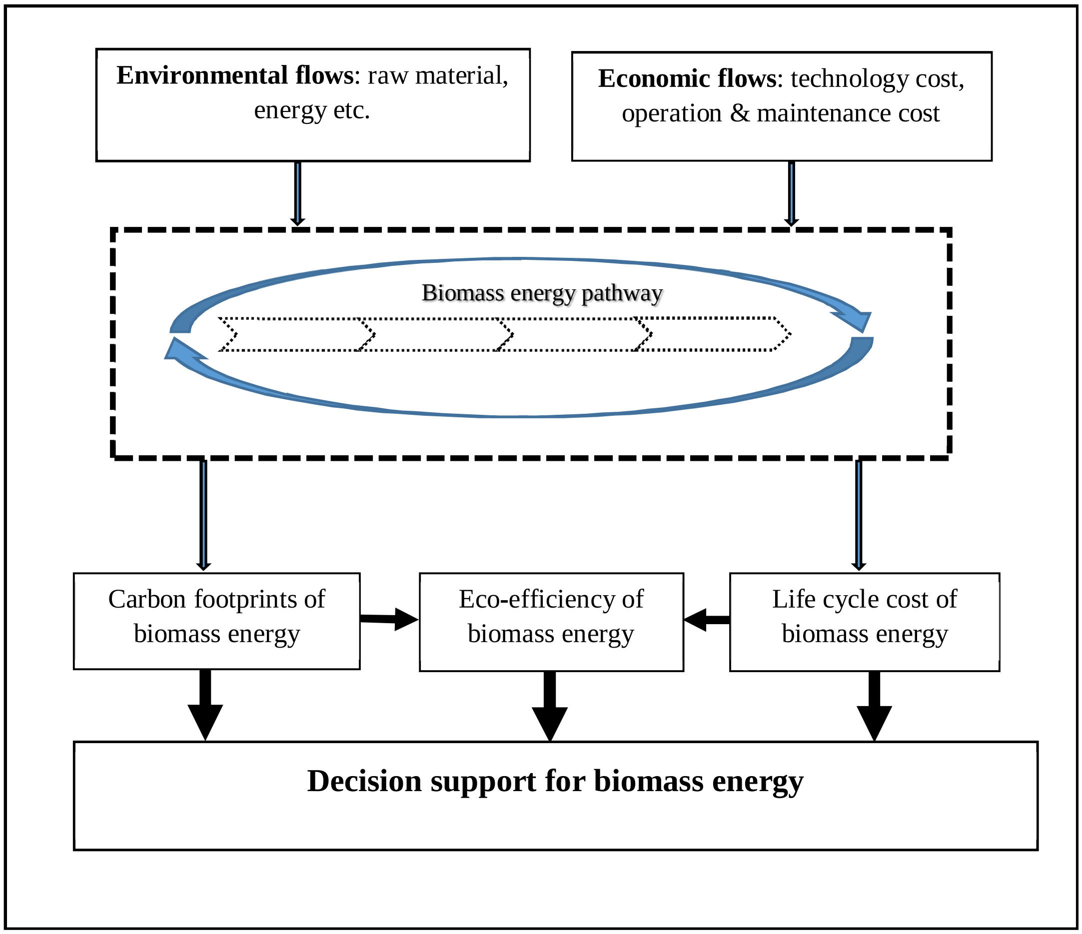

Figure 2.1: Conceptual framework

Source: Author

Furthermore, eco-efficiency is defined as a non-stop process of transformation so as to make, for instance, the extraction of raw materials, choice of investment, or the alignment of technological advancement in line with future and current needs (Steen, 2000). Following this argumentation, the present study combined the results of the LCA and LCC in order to provide a more comprehensive indicator of the different biomass energy chains. As such, the model illustrates that decisions on biomass energy need to take a multi-faceted approach. This provides useful information for policy making to stakeholders and policy makers in the biomass energy sector.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research methodology as well as the research sites: Kitui Central Sub-County in Kenya and Moshi in Tanzania. The chapter gives an in-depth description of the study sites and describes the sampling technique applied and the methods used for data collection and data analysis. The study applied the Life Cycle Assessment i.e. Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) to determine the carbon footprints and the cost per megajoule, respectively, of the selected biomass energy value chains. Lastly, the research determines the eco-efficiency of these value chains by integrating the LCA and LCC results.

3.2 Study Area

3.2.1 Kitui Central Sub-County

3.2.1.1 Location and Administrative units

Kitui Central Sub-County is located in Kitui County. Kitui County is located 170Km to the South East of Nairobi City. It borders Machakos and Makueni Counties to the West, Tana River County to the East, Taita-Taveta County to the South, and Embu and Tharaka-Nithi Counties to the North. Kitui Central Sub-County (Figure 3.1) has eight administrative wards namely Miambani, Kitui Township, Kyangwithya West, Mulango, Kyangwithya East, Itoleka, Katulani and Maliku.

3.2.1.2 Environmental Conditions

Kitui County's elevation ranges from 400m to 1800m above sea level. Its central part is characterised by undulating ranges divided by wide lowland areas with somewhat lower altitude ranging from 600m to 900m above sea level. Kitui County is classified as an arid and semi-arid area characterised by hot and dry climate. Approximately 40% of the entire zone is categorised as arable yet gazetted forests cover less than 1% (Kitui District Profile, n.d.).

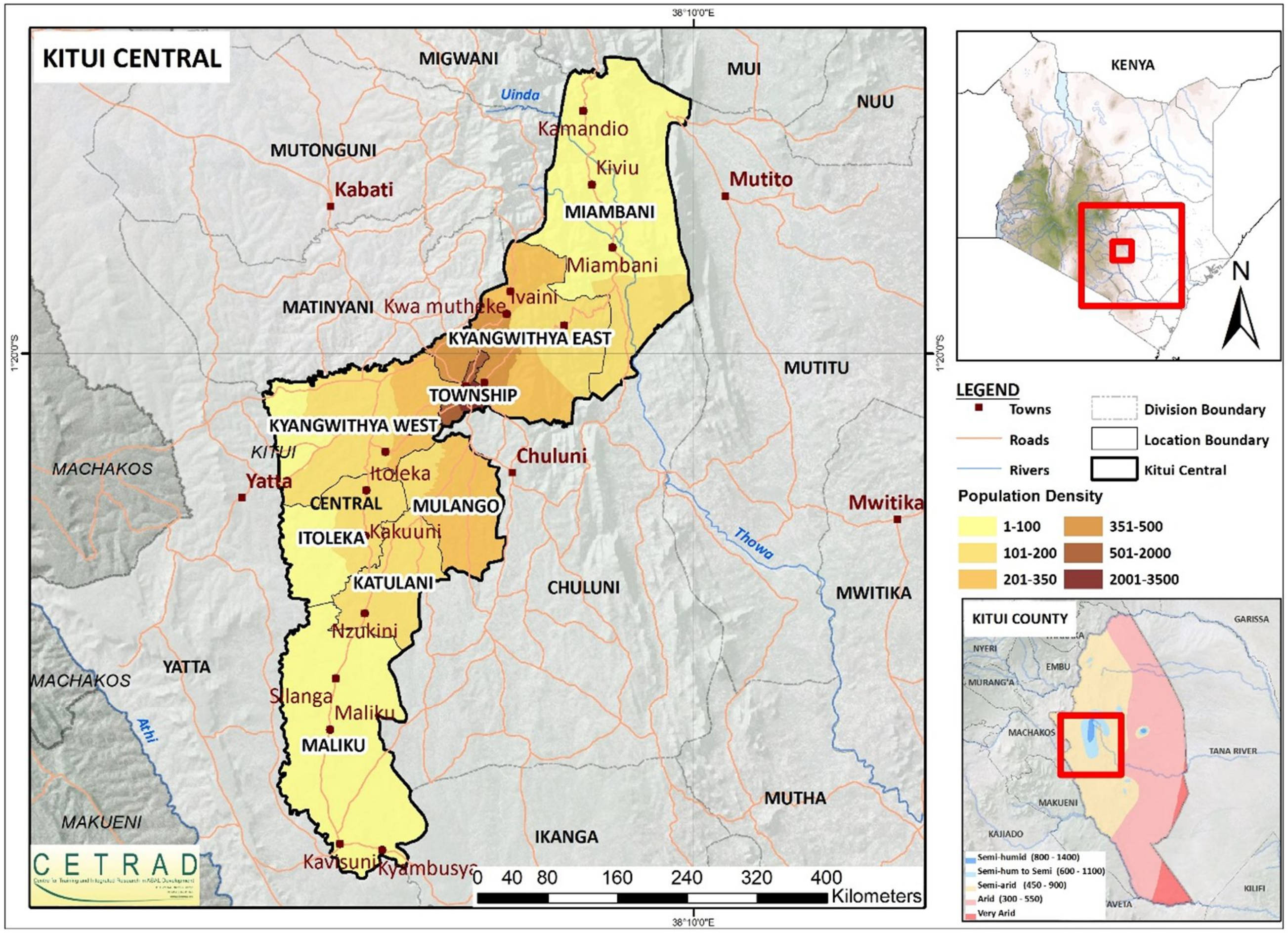

Figure 3.1: Location of Kitui Central Sub-County

Source: Centre for Training and Integrated Research in Arid and Semi-Arid Lands Development (CETRAD)

The rainfall pattern of Kitui County is bi-modal with annual averages ranging between 250mm to 1050mm. The area experiences long rains between March and May and are typically very unpredictable and unreliable (40% reliability). The short rains are experienced from October to December and are a bit reliable-60% reliability (County Government of Kitui, 2014). The county experiences varying high temperatures of between 14^0C to 34^0C all through the year. The maximum mean annual temperatures of Kitui County range between 26^0C and 34^0C and the minimum annual temperatures range between 14^0C and 22^0C. Mid- July to September and January to February are the hottest months (County Government of Kitui, 2014).

The county experiences increased frequencies of drought with increased socio-economic impacts that are aggravated by poor management of water catchment areas, inappropriate soil conservation measures, deforestation and general land degradation. Land degradations has worsened as a result of poor farming practices, overgrazing, lack of vegetative cover and increased pressure from human activities (County Government of Kitui, 2014). The livelihood of most residents depends on natural resources and small-scale rain-fed farming which is susceptible to the impacts of climate change and ecological degradation (Population Action International, n.d.). Rapidly growing population has placed huge stress on natural and environmental resources. It is important to note that with continued population increase, this pressure is expected to increase. The county is encountering severe water shortage. Recurrent famines have reduced water supply, resulting in many seasonal rivers, and eventually drying them totally. High levels of forest degradation have worsened the situation by severely shrinking the water catchment capacity. As such, one of the key environmental challenges faced by Kitui County is degradation of forests, which consequently leads to loss of biodiversity, and has been accelerated by population growth, rising poverty levels, agricultural expansion, overutilization of fragile ecosystems and overdependence on wood-based fuels and insignificant afforestation levels (Population Action International, n.d.).

3.2.1.3 Population and Economic Situation

The population density of Kitui County is 42 persons per km^2 and that of Kitui Central is 197 persons per km^2. The county is predominantly rural with 86% of the population estimated to be residing in rural areas. Availability and accessibility of water and fertility of the soils in addition to availability of social amenities that are reliable and economic opportunities greatly influences population distribution within the county. The county has a population growth rate of 2.1% which may exert pressure on the social and natural resources if not checked (County Government of Kitui, 2014).

The Human Development Index defined as "composite measure of growth that combines indicators of life expectancy, educational attainment and income" score of Kitui County is 0.53 and is lower than the nationwide average score of 0.56 (Population Action International, n.d.). Poverty is prevalent in the county with 591,600 residents living below the poverty line and a poverty incidence of 60.4% which is above the national average of 45.2% (Wiesmann et al., 2014). Human activities include clearing land for farming, establishing settlements, charcoal making and curving using indigenous trees which has caused massive deforestation with the most pronounced cause being felling of trees for charcoal burning. For instance, the region produces approximately 300,000 bags of charcoal annually resulting to loss of flora and fauna and massive degradation of land in the already vulnerable environment (Kitui District Profile, n.d.).

3.2.1.4 Energy Access

In Kitui County, 96.9% of the population use solid biofuels for cooking (Wiesmann et al., 2014). Firewood and charcoal is used by 89% and 8% of the households respectively as their primary source of energy used for cooking and only 1% and 2% of the residents use LPG and paraffin respectively for cooking (KNBS & SID, 2013). In Kitui Central 75% of the inhabitants use firewood and 17% use charcoal as their primary source of energy for cooking (KNBS & SID, 2013). Firewood is predominantly used in the rural areas while in the urban centres it is charcoal. Only about 3.8% of households in Kitui County and less than 1% in the rural areas are connected to the national grid which is quiet unreliable (County Government of Kitui, 2014).

3.2.2 Moshi

3.2.2.1 Location and Administrative boundaries

Moshi (Figure 3.2) is located in Kilimanjaro Region which hosts Mount Kilimanjaro. Tanzania has 26 regions one of them being Kilimanjaro Region with Moshi as its capital. It is bordered by Kenya to the North and East, to the South by the Tanga Region, to Southwest by the Manyara Region, and to the West by the Arusha Region.

3.2.2.2 Environmental and Agro-ecological conditions

Moshi is found in the intermediate zone of Kilimanjaro Region's agro-ecological zone which ranges from 900 to 1100 meters above sea level. The area receives annual rainfall which ranges between 800 and 1250 mm. The rainfall pattern is bimodal with a major rainy season between April and May and a short rainy season in September to November. The region also experiences the dry seasons twice a year between December and January and a minor one between July and August. The temperatures ranging from 20^0C to 30^0C (United Republic of Tanzania, 1998). The areas soil fertility is moderate thus supporting growing of coffee, banana, maize, and beans and is also appropriate for dairy cows, pigs, goats, rabbits and poultry keeping (United Republic of Tanzania, 1998). Poor farm management characterised by poor management system for instance non-use of soil erosion control methods, is a key driver of environmental degradation (United Republic of Tanzania, 1998).

3.2.2.3 Population and economic situation

The population density of Kilimanjaro region is 124 persons per square metres while the national population density is 51 persons per square metres (Tanzania National Bureau of Statistics, 2013). Moshi Municipal Council has a population of 184,292 whereas Moshi District Council has a population of 466,757 giving a total population of 651,049. The population growth rate of Kilimanjaro region was 1.8% between 2002 and 2012, which was less than the average national population growth rate of 2.7% (TNBS, 2013). The region experiences high rate of rural–urban migration since the agrarian sector has been unsuccessful in satisfying the economic needs of the rural populace.

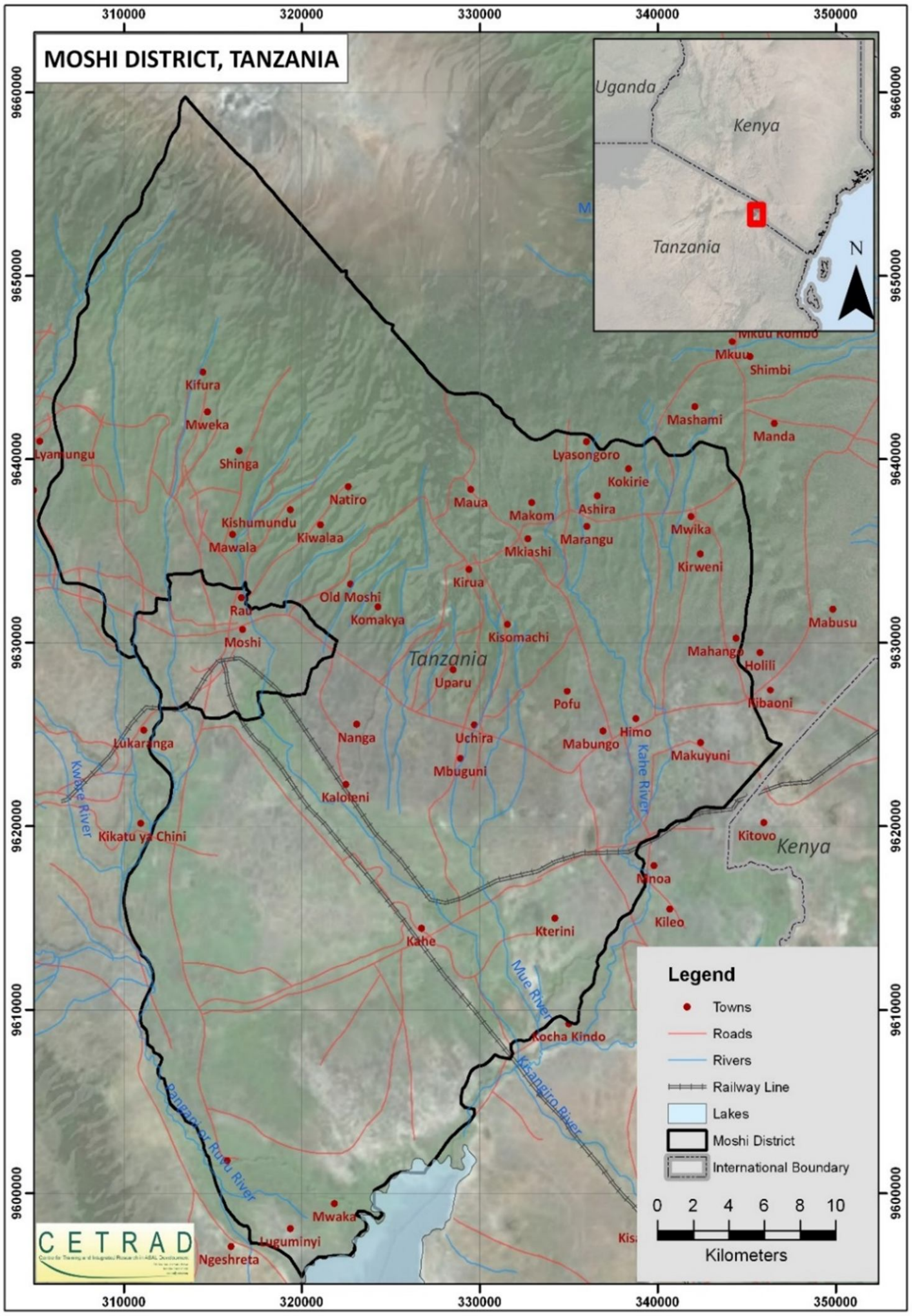

Figure 3.2: Location of Moshi municipality and Moshi District

Source: Centre for Training and Integrated Research in Arid and Semi-Arid Lands Development (CETRAD)

In addition, to lack of industrial development in the region and land scarcity (United Republic of Tanzania, 1998). The diminishing economic undertakings in the rural areas was as a result of dwindling prices of coffee, which consequently affected production volumes, and the extended famine tends to aggravate the situation. Currently, the economy is not performing well and relocation of the people to cities like Dar es Salaam, Arusha, Mwanza, Mbeya and elsewhere is profound. This has resulted to shutting down of agro-industries therefore affecting the economy of Moshi Municipal Council. Moshi rural depends on farming as the main source of livelihood. The crops cultivated include; maize, beans and bananas with some peoples still growing coffee. The inhabitants also keep cattle, goats, pigs and chicken. Rice farming is done under irrigation in lower Moshi. The three sources of water for irrigation include surface water, underground water and dams (United Republic of Tanzania, 1998).

3.2.2.4 Energy access

In Kilimanjaro region, all the towns are served with hydro-electricity with 52% of the villages connected to the national grid. Nonetheless, charcoal and firewood remain the leading source of energy for cooking for approximately 90% of both urban and rural and people (Felix & Gheewala, 2011).

3.3 The Methodology

3.3.1 Target Population

The study focused on firewood, charcoal, biogas, jaropha oil and crop residue briquettes. Additionally, the study considered specific technologies of producing and using these biomass energy carriers in Kitui and Moshi. As such, it was necessary to engage only the adopters of these technologies as summarised in Table 3.1.

Table 3.1: Selected biomass energy carriers and their production and consumption technologies

Biomass energy carrier	**Life cycle phase**	**Technology name**	
		Kitui	Moshi
Firewood	Production	None	
	Use	Three stones, *maendeleo*, rocket, *envirofit* stove	Three stones, *kuni-chache, okoa*
Charcoal	Production	Basic earth mound kiln Improved Basic Earth Kiln	
	Use	Kenya Ceramic Jiko (KCJ)	*Sazawa* charcoal stove
Biogas	Production	Plastic biogas digester	VACVINA
	Use	Biogas burner	
Jatropha oil	Production	Manual jatropha oil press Diesel powered jatropha oil press	
	Use	Jatropha oil stove	
Crop residue briquettes	Production	Manual briquette press Diesel powered briquette press	
	Use	Briquette stove	

3.3.2 Sampling Procedure

The study applied purposive sampling. The application of this design was influenced by the fact that there was a deliberate choice of participants in this study. Since the focus of this study was on specific selected biomass energy production and consumption technologies, snowballing was applied as a method of respondent identification where the selected technologies were available in the field.

3.3.3 Sources of Data

Data for the LCA included feedstock type in use, its sources, mode of harvesting, transport mode used, wastes and emissions generated. The data used for the LCC included technology acquisition costs, replacement, operation and maintenance costs. Since the focus of this study was alternative biomass energy value chains, it is worthwhile to note that some technologies and consequently their respective value chains may not have already been familiar to the residents of Kitui and Moshi at the time of the study. Where technologies were not available, the modelling was done using data from literature, reports and *Eco-invent* database. Selection of literature data was based on similarity in geographical contexts and technology and efficiency of selected biomass energy production and consumption technologies.

The emission of various technologies were derived from literature, *Ecoinvent* databases and also using the “IPCC default emission factors” (IPCC, 2006) and specific fuel consumption of a stove. The *Ecoinvent* database accommodates data for products, services and processes often used in LCA case studies (Frischknecht et al., 2007). The database lays a foundation for the LCA study by providing process datasets for products in areas such as energy supply, agriculture, transport, biofuels and biomaterials, construction material, wood and waste treatment (Ecoinvent, n.d.). This, therefore, helps in the calculation of their environmental impacts.

3.3.4 Methods of Data Collection

The study used primary and secondary data and data from *Ecoinvent* version 3.1 databases (Weidema et al., 2013). Primary data was collected using a set of structured questionnaire (see Appendix 1). The questionnaires were administered to biomass energy producers and consumers targeting the users of selected biomass energy technologies. The number of interviews conducted is illustrated in Table 3.2 and 3.3 for Kitui and Moshi respectively. Information was also obtained by conducting expert interviews using an interview guide (See Appendix 2). In Kitui, experts interviewed included representatives from Kenya Forest Service, Kitui Renewable Energy Centre, Musekavo Community Forest Association, and a consultant on rocket stoves. In Moshi representatives were from Nandra Engineering Company, Kilimanjaro Industrial Development Trust, Tanzania Forest Service, Tanzania Forest Research Institute and Jatropha Products Limited. Additional data on the technologies was also obtained from Practical Action and Tanzania Traditional Energy Development Organisation.

Table 3.2: Data collection in Kitui

	Fuel name	**Name of production technology**	**Number of interviews conducted**	**Name of consumption technology**	**Number of interviews conducted**	**Comments (*Where necessary*)**
Kitui	Firewood	None	0	3 stones fireplace	5	Firewood is used as it is without any processing, therefore, no technology selected for it
				Maendeleo stove	5	
				Rocket stove	5	
				Envirofit stove	5	
	Charcoal	Basic earth mound kiln	5	unimproved charcoal stove	5	
		Improved earth mound kiln	0	Kenya Ceramic Jiko	5	Improved earth kiln not yet in use
	Biogas	Plastic biogas digester	0	Biogas burners	5	Plastic biogas digester not yet in use
		Plastic tubular digester	5			Plastic tubular digester not selected for study but interviews done to give an idea of the biogas value chain in Kitui for modelling purposes.
	Jatropha oil	Manual oil press	0	*Biomoto* stove	0	Both presses and stove not yet in use.
		Diesel oil powered press	0			
	Crop residue briquettes	Manual briquette press	2	Briquette stove	0	The manual briquette press user was using charcoal dust as the raw material rather than crop residues. However interviews done to give an overview of the manual briquette press for modelling purpose.
		Diesel powered briquette press	0			Diesel briquette press not yet in use
Total			**12**		**35**	**47 questionnaires administered**

Table 3.3: Data collection in Moshi

	Fuel name	**Name of production technology**	**Number of interviews**	**Name of consumption technology**	**Number of interviews**	**Comments (*Where necessary*)**
Moshi	Firewood	None	0	3 stones fireplace	5	No production technology selected
				Kuni-chache stove	5	
				Improved *okoa* stove 1(with water heater)	5	
				Improved *okoa* 2 (with no water heater)	4	
	Charcoal	Basic earth mound kiln	5	unimproved charcoal stove	5	
		Improved earth mound kiln	0	*Sazawa* charcoal stove	0	Improved earth kiln and *sazawa* stove not yet in use
	Biogas	VACVINA biogas digester	0	Biogas burners	0	VACVINA biogas digester not yet in use
	Jatropha oil	Manual press	0	*Biomoto* stove	0	Both presses and stove not yet in use.
		Diesel powered press	0			
	Crop residue briquettes	Manual briquette press	0	Briquette stove	0	Both presses and stove not yet in use
		Diesel powered press	0			
		Industrial briquette production	1	Gasifier briquette stove	1	Not selected but interview done to give an overview of crop residue briquette making and use in Moshi
Total			**6**		**25**	**31 questionnaires administered**

3.3.5 Methods of Data Analysis

Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) techniques are applied respectively to evaluate the carbon footprints and the life cycle costs of the selected biomass energy value chains as shown in Table 3.4. The methods applied are explicitly defined in sections 3.3.5.1 and 3.3.5.2. The LCA and LCC assumptions applied in this study are explicitly discussed in detail in chapter 4. The LCA and LCC results are thereafter integrated to determine the eco-efficiency of these selected biomass energy value chains as described in section 3.3.5.3. The LCA analysis is done using *Simapro* software developed by Pré (PRe, 2015). On the other hand, the LCC and the eco-efficiency analysis are done using Ms Excel 2010. The results are presented by objectives in chapters 5, 6 and 7 respectively.

Table 3.4: Summary of data analysis

Objective	**Data type**	**Data analysis method**
Carbon footprints	*Raw material inputs*: feedstock type & its source, feedstock amount, water, mode of harvesting, transport mode used, distance travelled *Output*: emissions and wastes	Life Cycle Analysis (LCA)
Life cycle costs	Technology acquisition costs, operation and maintenance costs, labour hours used for feedstock collection, labour hours used for biomass energy preparation	Life Cycle Costing (LCC)
Eco-efficiency	Integrated LCA and LCC data	Integration of LCA and LCC results

3.3.5.1 Life Cycle Assessment

"Life Cycle Assessment (LCA) addresses the environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, end of life treatment, recycling a and final disposal" (ISO, 2006a). According to the LCA methodology, the raw material and energy, numerous emission types and other significant elements associated with a particular product or process can be measured over the whole life cycle, largely from an environmental perspective. According to ISO (2006b), LCA studies include four phases (Figure 3.3): 1) Definition of the goal and scope of the study; 2) Analysis of the inventory; 3) Assessment of the impact; and 4) Interpretation of the results.

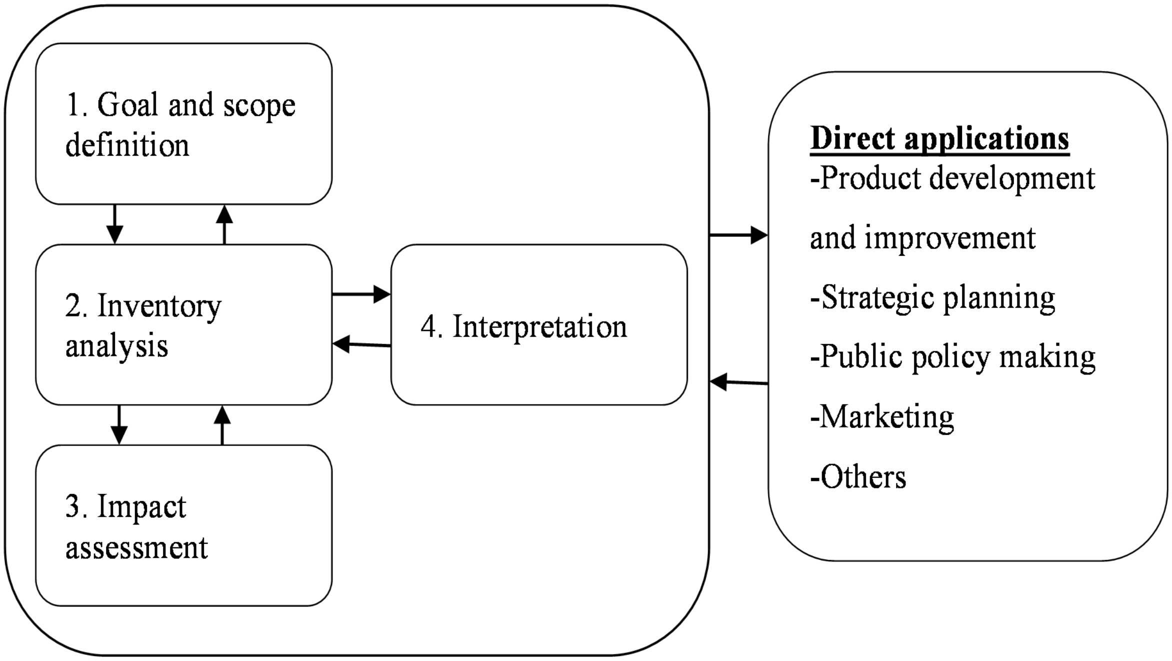

Figure 3.3: LCA phases and its application according to ISO 14040 (ISO, 2006b)

Definition of the goal and scope is the initial stage of an LCA study. In this point, the objectives of the LCA study are defined clearly while stating the intended application of the study. During this stage, the scope of the study should be adequately described so that the boundaries and all other details of the study are well-matched and enough to take care of the outlined goal.

Life cycle inventory (LCI) analysis phase is the second stage which encompasses the gathering and quantification of inputs and outputs for a product through its life cycle. This phase includes data gathering and calculation techniques to compute significant inputs and outputs of the product system. Life cycle impact assessment (LCIA) is the third stage and evaluates the importance of possible ecological effects by using the LCI results. This procedure involves linking inventory data with exact environmental impact categories and category indicators.

Life cycle interpretation is the final stage of LCA in which the results from the inventory analysis and the impact assessment are reflected together or, in the case of LCI studies, the results of the inventory analysis only. The interpretation stage ought to provide results that are in line with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal (ISO, 2006b).

3.3.5.2 Life Cycle Costing

Life cycle costing (LCC) is an “Assessment of all costs related to a product or service, over the entire life cycle, from production through use until disposal” (Ciroth & Franze, 2009). It is useful in checking and managing costs over the product’s life cycle and may refer to previous products systems to collect data for prospective products (Lichtenvort et al., 2008). The life cycle analysis is presented as cost per megajoule. The analysis of life cycle costs in this study, therefore, assumes steady state models which lack temporal specification and assumes all technologies remain constant in time while adopting substance flow analysis (Huppes et al., 2008). The steady state model uses the LCA life cycle inventory of the selected biomass energy value chains and assumes the same functional unit as that of the LCA (Lyrstedt, 2005) i.e. 1 megajoule of heat delivered to cooking pot. The procedure followed for calculating the LCC of the selected biomass is outlined in section 3.3.5.2.1. Non-monetary elements are not changed to monetary values because they are catered for in ecological terms through the results of the impact assessment according to ISO 14040/44 (2006) or through a separate social life cycle assessment (Andreas et al., 2008).

3.3.5.2.1 Energy costs per MJ delivered to pot

In order to determine the energy cost per reference unit (cost per MJ), the following steps for carrying out the LCC according to (Rebitzer & Nakamura, 2008) are applied for each value chain:

1) Identification of the unit processes;
2) Assignment of costs to the particular product flows of the unit process with the process output as a reference unit;
3) Identification of additional costs of the unit process as determined in stage 1 that vary amongst the studied alternatives;
4) Allocating costs to added process identified in step 3;
5) Calculation of the costs per unit process by multiplying the cost per reference unit from steps 2 and 4 with the total amounts of the process outputs for giving the reference flows of the whole product system; and
6) Aggregation of the costs of all unit process over the complete life cycle.

3.3.5.3 Eco-efficiency assessment

Eco-efficiency as used in the present study, is a concept that brings together the two dimensions of biomass energy: ecology and economy. It determines the ecological performance of the studied biomass energy while also considering its economic performance. In this study, the environmental performance of biomass energy is measured using its carbon foot prints (kgCO_2eq/MJ), while the economic viability is assessed by its cost per unit (US$/MJ). The eco-efficiency analysis is done by plotting both the carbon footprints and the cost per MJ on an XY scatter plot chart in Excel.

3.3.6 Methodological Scope and boundary

The study analyses different biomass value chains. The LCA/LCC community uses the term product system that embraces the entire value chain. In this study, feedstock collection, feedstock processing, transport and use form the unit processes of biomass energy value chains as shown in figure 3.4. The emission of various technologies were derived from literature, *Ecoinvent* databases and also using the "IPCC default emission factors" (IPCC, 2006) and specific fuel consumption of a stove. The *Ecoinvent* database lays a foundation for the LCA study by providing process datasets for products in areas such as energy supply, agriculture, transport, biofuels and biomaterials, construction material, wood and waste treatment (Ecoinvent, n.d.). This, therefore, helps in the calculation of their environmental impacts.

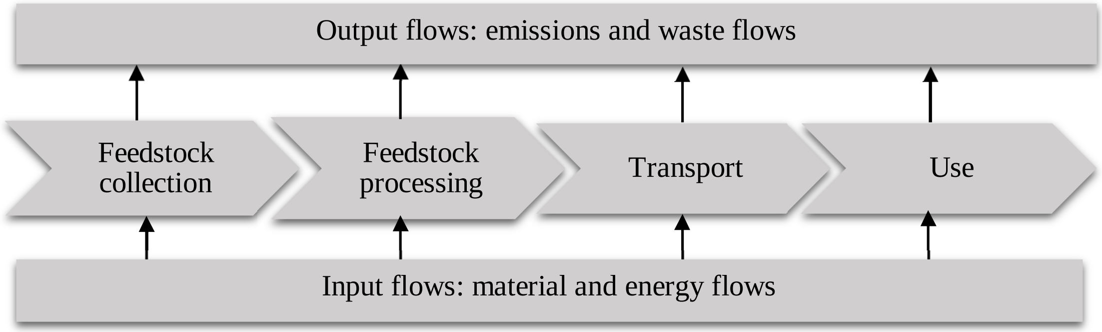

Figure 3.4: Biomass energy product system

The analysis of the rural context excludes the transport phase. The exclusion of transport phase in the rural context analysis is centred on the supposition that rural households have the potential to produce their own energy, therefore, excluding the need for its transportation. The life cycle cost analysis of the urban context uses the product cost .This is due to the fact that in the urban areas, households may not have the capacity to produce their own energy and, therefore, the need to purchase it. In addition, this excludes double counting of costs since it is assumed the purchasing price of fuels includes the production and transport costs. Feedstock collection as referred to in this study is the process of harvesting the raw biomass material needed to make the selected biomass energy fuel i.e. firewood and charcoal (wood), biogas (cow dung), jatropha oil (jatropha seeds from hedges) and crop residue briquettes (maize cobs and rice husks).

Feedstock processing, where applicable, refers here to the conversion of raw biomass material to usable form of biomass energy carrier. Transport, where applicable, defines the transport system/mode used to transport biomass energy carrier to the household for use. Use phase here is defined as the combustion of biomass energy fuel to provide heat necessary for cooking in the household.

3.7.1 Function, functional unit and reference flow

A system may have numerous possible functions depending on the goal and scope of the study. The functional unit defines the quantification of the identified functions of the product. The main purpose of a functional unit is to offer a reference to which the inputs and outputs are linked. This reference is essential to guarantee comparability of both the LCA and LCC outcomes of the biomass energy value chains as illustrated by Figure 3.5.

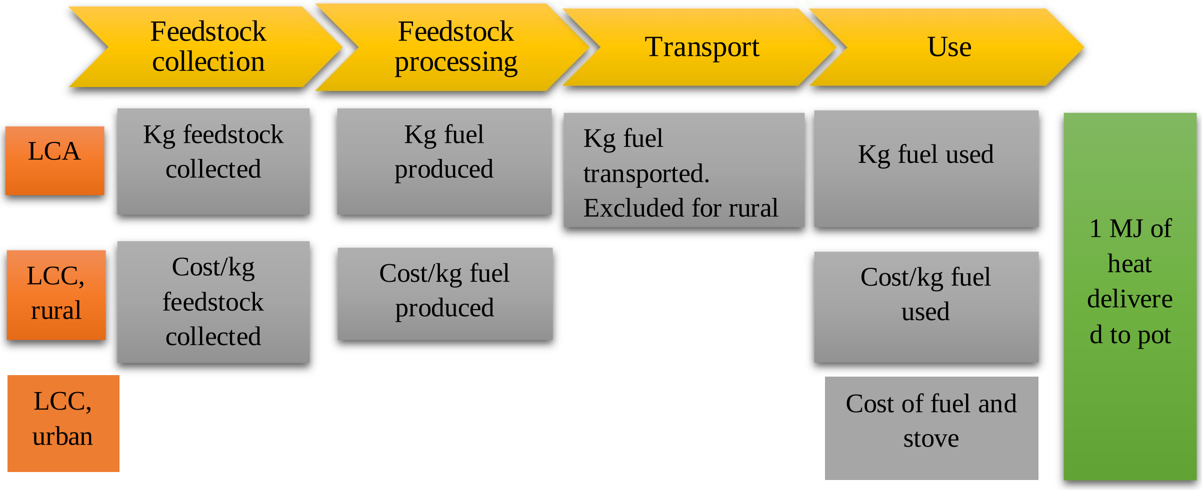

Figure 3.5: Reference flows and functional unit of the life cycle stages of biomass energy

In this study, the biomass energy fuel is intended to provide heat for cooking in the household. It applies a functional unit of 1 MJ of heat delivered to cooking pot. In order to achieve the function of cooking, different processing steps are required each with its own reference flow.

3.3.7 LCIA method and impacts

LCA assesses various categories of environmental impacts such as greenhouse gas emissions, acidification potential, photochemical ozone formation, human toxicity, stratospheric ozone depletion and eco-toxicity, nutrient enrichment (Heidi & Stranddorf, 2005). However, as described in section 1.7, this study evaluates only the carbon footprint of the particular biomass energy pathways. Carbon footprints, or the quantities of greenhouse gas emissions associated with specific activities, are linked with climate change and its effects. The analysis is based on the single issue indicator for Global Warming Potential (GWP 100a) of the Intergovernmental Panel on Climate Change (IPCC, 2013).

CHAPTER FOUR

COMPARED BIOMASS ENERGY VALUE CHAINS

4.1 Introduction

This chapter gives an in-depth description of the biomass energy value chains studied while also indicating the selected biomass energy technologies of production and consumption. The assumptions applied in the study are also presented in this chapter for a better understanding of the subsequent chapters. Since the emphasis was on energy used for cooking in the urban and rural contexts, the system boundaries were adjusted to every form of setting. For rural settings, investigations comprised collection of the feedstock, processing of the feedstock, and consumption, while transport was excluded with the presumption that families made their own biomass energy.

For the urban settings the carbon foot printing assessment included collection of the particular feedstock, processing of the feedstock, transport of the biomass fuel, and utilisation of the biomass fuel. However, the life cycle costing in the urban context only included the use phase since the study assumed that the purchasing price of the energy carriers already sums up the upstream costs. Investigation of biogas is limited to rural settings because biogas is generated and used at the point of production a situation which is currently not feasible in the urban settings in Kenya and Tanzania. The functional unit adopted applied for the biomass energy pathways in this research was 1 megajoule (MJ) of heat transferred to the cooking pot. Table 4.1 describes the specific assumptions for each of the described value chains.

4.2 Firewood value chain

Firewood is wood that does not undergo any form of transformation. This research, therefore, focussed on the technologies used for the consumption of firewood at the household level. In this study, two scenarios of the firewood value chains were modelled; the improved and unimproved firewood value chains. The unimproved value chain assumed unsustainable wood harvesting practices and usage of the three-stone fireplace characterised with low thermal efficiency. The improved value chain, by contrast, assumed sustainable wood harvesting practices and use of an improved firewood cooking stove, as described in the following sub-sections.

4.2.1 Feedstock Collection

Firewood is often obtained by cutting down trees which are chopped into smaller pieces, then stored preferably in the kitchen (Plate 4.1) for use by households.

Scenario 1: Unimproved Firewood Value Chain

The unimproved firewood pathway was presumed to comprise unselective cutting of trees for provision of firewood, devoid of any meaningful reforestation measures that ensure regrowth of trees. If reforestation or replanting of trees is not done, the biogenic carbon dioxide emissions linked with the burning of firewood in this pathway is considered with similar global warming potential as that of carbon dioxide from fossil sources. This symbolises the realism of unlawful cutting of trees for provision of firewood, consequently resulting to overexploitation of forest resources and eventually their degradation.

Scenario 2: Improved Firewood Value Chain

The improved pathway, by comparison, was presumed to comprise ecologically viable wood extraction methods which allow for the regrowth and replanting of trees. It must, however, be noted that even when reforestation of trees is done immediately after harvesting, it would still take a complete rotation period before the biogenic emissions of carbon dioxide are re-absorbed. Nonetheless, the short-term rise in atmospheric carbon dioxide concentration has to be accounted for. For this reason, the study adopted the Cherubini et al., (2011) accounting method which presumes biogenic carbon dioxide emissions linked with the combustion of firewood. Consequently, biogenic carbon dioxide emissions are catered for with a characterisation factor of 0.18 which is about one-sixth of the global warming potential of carbon dioxide generated by fossil source while presuming an average rotation period of 44 years.

Table 4.1: Biomass energy pathways, life cycle phases, assumptions, and source of data

Value chains		Unimproved firewood	Improved firewood	Unimproved charcoal	Improved charcoal	Biogas	Jatropha oil, manual press	Jatropha oil, diesel press	Briquettes, manual press	Briquettes, diesel press
Feedstock collection	LCA assumptions	-Unsustainable wood harvesting: no regrowth -Manual harvesting of wood	-Sustainable wood harvesting: regrowth and use of dead wood -Manual harvesting of wood	-Unsustainable wood harvesting: no regrowth -Manual harvesting of wood	-Sustainable wood harvesting: regrowth -Manual harvesting of wood	-Cow dung: waste product of cattle keeping -Manual harvesting of cow dung	-Seeds from jatropha hedge -Manual harvesting of jatropha seeds	-Seeds from jatropha hedge -Manual harvesting of jatropha seeds	Maize cobs (Kitui) and rice husks (Moshi): waste product from maize/rice farming and waste paper -Manual collection of crop residues	-Maize cobs (Kitui) and rice husks (Moshi): waste product from maize/rice farming -Manual collection of crop residues
	Ecoinvent process adopted	Roundwood {GLO} |harvest, primary forest|Alloc Rec,U” which represents fuel wood extraction using IPCC default biomass conversion and expansion factors (IPCC, 2006) and wood densities of acacia tree species. The model presumes that not all the wood is used after extraction for instance the roots, leaves, branches which in the process decomposes thus emitting carbon dioxide.								
	LCC assumptions	Labour hours & cost	Labour hours & cost	Labour hours and cost	Labour hours and cost	Labour hours and cost KI: free range system MO: zero grazing	Labour hours and cost	Labour hours and cost	Labour hours and cost	Labour hours and costs
Feedstock processing	Technology	None		Basic Earth Mound Kiln	Improved Basic Earth Kiln	Plastic digester and VACVINA biogas digesters	Manual oil press	Diesel powered oil press	Manual briquette press	Diesel powered briquette press
	Efficiency			13.1% (Gmunder 2014)	20% (Beukering et al; Jetter 2012	75% (Charles, et al., 2011)	60% (FACT Foundation, 2010)	80% (FACT Foundation)	100 % (PA)	100 % (PA)

	Emission source/ *Ecoinvent name*							Diesel burned in diesel electric generating set		Diesel burned in diesel electric generating set
	LCA assumptions	None		Labour hours and cost, Technology purchase cost	Labour hours and cost, Technology purchasing and maintenance cost	Labour hours and cost, Technology purchasing and maintenance cost	Labour hours and cost, Technology purchasing and maintenance cost	Labour hours and cost, Technology purchasing and maintenance cost	Labour hours and cost, Technology purchasing and maintenance cost	Labour hours and costs, Technology purchasing and maintenance cost
	LCC assumption	None since no technology is involved	None since no technology is involved	Labour hours and cost	Labour hours and cost	Technology installation (materials, skilled and unskilled labour), annual maintenance, labour hours and cost	Technology purchase price, annual maintenance, labour hours and cost	Technology purchase price, annual operation and maintenance, labour hours and cost	Technology purchase price, annual maintenance, labour hours and cost	Technology purchase price, annual operation and maintenance, labour hours and cost
Transportation	Transport mode and distance	Rural: None Urban: Bicycle (30 km)	Rural: None Urban: Bicycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	None	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)
	Ecoinvent name	Transport, bicycle/AF U		Transport scooter			Transport scooter			
	LCC assumptions	Not included								

	Cooking device & stove efficiency (%)	3 stones fireplace: 12.5 %	*maendeleo:* 18%, *envirofit:* 29.7% rocket: 28% *kuni-chache*: 24%, *okoa*: 40% [PA & TaTEDO]	Unimproved charcoal stove: 24 %	Kenya ceramic Jiko: 32%, *sazawa* charcoal stove :44 %	Biogas burner: 55 % stove efficiency	Jatropha oil stove: 40 % stove efficiency,	Briquette stove: 32 % stove efficiency (adopted efficiency of KCJ)
	Energy content, MJ/kg	18		28		17.71	39.8	Maize cob briquette: 17.65 Rice husk briquette: 18.15
	Lifespan (years)	1 year (where clay bricks are used, as is the practice)	*Maendeleo* (4.5) Envirofit (5.5) Rocket (5) *Kuni-chache* (2) Okoa (8)	1.5	3	10	25	3
	Sources of emission data	Calculation using IPCC default emission factors (IPCC, 2006) and stove specific fuel consumption' (GACC, n.d.; Jungbluth, 1997; MacCarty et al., 2008; Jetter & Kariher, 2009)		(MacCarty et al., 2008; Jetter 2012; Gmuder et al., 2014)		(Smith, et al., 2000; Afrane & Ntiamoah, 2011)	Calculation using IPCC default emission factors (IPCC, 2006) and stove specific fuel consumption	
	LCC assumption	Rural context : Cost of cooking device Urban context: Cost of cooking device and fuel cost						
Functional unit		1 MJ						

Plate 4.1: Storage of firewood in a kitchen

For both firewood value chain scenarios, it is important to note that wood harvesting is done manually using axes and machetes. The axes and machetes used for wood harvesting have no emissions at this stage and, hence, free of environmental load. Their use is also not exclusive to firewood harvesting, therefore, the LCC calculations did not allocate the costs to firewood collection

4.2.2 Feedstock Processing

Firewood is used as it is without undergoing any form of processing, therefore, no production technology was considered in this study. Consequently, no inputs, outputs and costs were considered for this phase.

4.2.3 Transport

In the rural areas, firewood is usually collected and carried on the back (Plate 4.2) especially by women and children who are tasked with the burden of firewood collection (WEO, 2006). Firewood is often transported to the nearby urban areas such as Kitui and Moshi towns using bicycles (Plate 4.3). The LCA thus included transport analysis for the urban context only. The bicycle was assumed to carry five loads of firewood stack together each weighing approximately 17 kilograms (field measurement done in Moshi).

Plate 4.2: Transportation of firewood using human labour

Plate 4.3: Transportation of firewood using bicycle

4.2.4 Use/Consumption

Scenarios 1: Unimproved firewood value chain

The LCA study adopted the three stones fireplace (Plate 4.4) to the unimproved firewood value chain in both Kitui and Moshi. The three stones fireplace, *also known as "mafiga matatu"* in Swahili, is characterised by poor combustion efficiency of 12.5% (Practical Action data) which results in excessive firewood use. The unimproved firewood value chain considered carbon dioxide emissions from fossil sources linked with burning of firewood as per the accounting technique of Cherubini et al (2011), by applying a characterisation factor of one.

Scenario 2: Improved firewood value chain

Improved wood stoves such as the *maendeleo* rocket and *envirofit* stoves in Kitui and the *kuni-chache* and the *okoa* stoves in Moshi were adopted in the improved firewood value chain (Plate 4.5)**.**

Plate 4.4: The three stones fire place

The improved firewood pathway, by comparison, was presumed to comprise ecologically viable firewood harvesting practices, enabling regrowth and replanting of trees coupled with the use of an enhanced firewood cooking devices. Consequently, biogenic carbon dioxide emissions were catered for with a characterisation factor of 0.18, which is about one-sixth of the global warming potential of carbon dioxide generated by fossil source while presuming an average rotation period of approximately 44 years (Cherubini et al., 2011). However, where dead wood was adopted as a source of fuel, the study applied a characterisation factor of zero, which assumed carbon neutrality. In this study fuel energy content of 18 MJ/kg has been used for firewood.

Plate 4.5: Improved firewood stoves

In both the traditional and the improved firewood value chains and in both research sites, the wood and the wood stoves were considered as the inputs, while emissions and wastes were considered as outputs in the LCA study. In the rural context, the LCC analysis included the cost of purchasing the specific stoves while in the urban context, it included the cost of purchasing both the stoves and the firewood. The LCC analysis in the urban context included on the use phase along the biomass energy value chains. Consideration of the use phase only was influenced by the fact that the market price of the firewood was inclusive of all the upstream costs, and their inclusion would, therefore, amount to double counting of costs.

4.3 Charcoal Value Chain

Charcoal, which is a solid residue, is derived from the carbonization of wood. Virtually all the charcoal in humid countries are made using above ground tree biomass, indicating that entire or portions of trees must be cut down (Chidumayo & Gumbo, 2013). Charcoal is mostly used in urban areas whereas its production is done in the rural areas. Here as is the case for firewood value chain, two scenarios of the charcoal value chains were modelled; the improved and unimproved charcoal value chains. The unimproved charcoal pathway was presumed to comprise unsustainable wood extraction methods, use of the basic earth mound kiln (also referred to as the traditional kiln), coupled with the use of a traditional (metal) stove of very low thermal efficiency.

On the other hand, the improved value chain was assumed to comprise sustainable wood harvesting practices, the use of improved basic earth mound kiln and use of an improved charcoal cooking stove, as described in the following sections. It is of great importance to note that while modelling the firewood and charcoal scenarios, the assumptions considered an extensive probable ranges of carbon footprints, whereby the traditional charcoal pathway portrays the worst-case scenarios and the improved value chains demonstrating best-case scenarios. Analysis of the worst-case situation helps recognising points of influence for the purpose of refining the different phases of the pathway being studied.

4.3.1 Feedstock Collection

Scenario 1: Unimproved Charcoal Value Chain

The traditional charcoal pathway was presumed to comprise of wood extraction practices that are not ecologically sound. These practices do not provide an opportunity for regrowth of trees and, therefore, combustion of wood from such a source is hereby considered fossil source of carbon dioxide emission. Once again, these practices as portrayed in the model assumptions replicate the veracity of unlawful cutting of trees/clearing of forests for the purpose of charcoal, which consequently causes forest degradation as a result of overexploitation of forest resources.

The LCA study used the wood harvesting practices in Miambani, Kitui to model the charcoal value chain in Kitui while that of Moshi was adopted from Kahe ward. This is because at the time of field data collection, these areas were known as charcoal producing areas within the surrounding. Miambani and Kahe areas have pockets of indigenous tree species that the charcoal makers still rely on as their source of wood for charcoal production. The use of indigenous tree species, such as the *Acacia* species, for charcoal production is dominant due to their perceived good quality charcoal often termed as “heavy charcoal” by the charcoal users. It is important to note here that these charcoal production activities were not authorised. For instance, in Kilimanjaro region where Moshi lies, charcoal production is totally banned. However, the production still goes on illegally in Kahe ward where Kahe 1 and Kahe 2 forest reserves are found. At the time of field interviews the charcoal producers were not replanting trees after cutting. Reliance on indigenous tree species without deliberate effort of replanting exposes these areas to massive deforestation as is being experienced in Kahe already.

Scenario 2: Improved Charcoal Value Chain

For the improved charcoal pathway, the study presumed use of sustainably extracted wood which the study modelled to involved parallel extraction and planting of trees concurrently so as to curb overexploitation of forest resources. In both scenarios within the two case study sites, wood for charcoal production is harvested manually using axes and, therefore, no inputs of machineries are included. The life cycle costing was done considering the labour hours used for wood harvesting. The cost of the axe and machetes were however not included since their use is not exclusive to wood harvesting for charcoal production. This created difficulty in allocating their costs to wood harvesting for charcoal production.

4.3.2 Feedstock Processing

Scenarios 1: Unimproved Charcoal Value Chain

The basic earth mound kiln represents the unimproved charcoal value chain with low wood conversion efficiency of about 11-25% (Felix & Gheewala, 2011). In this study an average efficiency of 13.1% for the basic earth mound kiln as measured in Kilosa, Tanzania by Gmünder et al. (2014) has been used. This kiln is essentially made up of wood arranged as desired (Plate 4.6), which is then covered by grass, branches, and a last coating of soil during the firing period.

Scenario 2: Improved Charcoal Value Chain

The improved earth kiln (Plate 4.7), which in this LCA study, represents the improved charcoal value chain is, to date, however not in use in both study sites**.** The study, however, went ahead to compare it with the basic earth mound kiln because of its potential to reduce emission due to its improved wood conversion efficiency averaging 19.6% (Beukering et al., 2007; Gmünder et al., 2014). The Improved Basic Earth Kiln (IBEK) is essentially a traditional kiln which is improved by regulating air supply thus monitoring inlet air and regulating the expended air through one vent (Malimbwi & Zahabu, 2008). It requires an additional metal chimney and a systematic stacking of the wood. On the other hand, LCC analysis for feedstock processing included labour hours, which were translated to costs, in addition to the cost of the chimney used with the IBEK.

Plate 4.6: Wood at a kiln site

Plate 4.7: Improved basic earth kiln

4.3.3 Transport

The transportation of charcoal can be done by a range of vehicles from the very large trucks to motorcycles. It can also be done by bicycles and also by human labour. However, this study modelled charcoal transport using the motorcycle (Plate 4.8).

Plate 4.8: Charcoal transport using a motorcycle

This was primarily influenced by the fact that transporting more than four bags of charcoal in Kitui is prohibited and thus the use of the motorcycles became the only feasible option. Since charcoal production is totally banned in Kilimanjaro Region, the transportation of charcoal using motorcycle to the nearest urban areas was the easiest. In addition, motorcycle transportation has in the recent past become the most common mode of transport in the study sites like in other areas across the two countries.

4.4.4 Use /Consumption

Scenarios 1: Unimproved Charcoal Value Chain

The unimproved (metal) charcoal stove (Plate 4.9) represents the unimproved charcoal value chain in Kitui and Moshi. The life cycle inventory of the unimproved charcoal stove is based on a stove efficiency of 24% and a lifespan of one and a half years (Practical Action data).

Plate 4.9: Unimproved charcoal stove

Scenario 2: Improved Charcoal Value Chain

The improved charcoal stoves; Kenya Ceramic Jiko (Kitui) and *sazawa* charcoal stove (Moshi) (Plate 4.10), represent the improved charcoal value chain. The KCJ has a single clay lining while the *sazawa* stove has a double clay liner beneath the metal cladding.

Kenya Ceramic Jiko

Sazawa charcoal stove

Plate 4.10: Improved charcoal stoves

The KCJ has a thermal efficiency of 32% (Jetter et al., 2012), while that of the *sazawa* charcoal stoves is 44% (TaTEDO data), each having a lifespan of three years. Calculations were based on charcoal energy content of 28MJ/kg. Based on the assumption of regrowth, the emission of biogenic carbon dioxide linked with the burning of charcoal in the improved charcoal pathway was factored in, once more according to the recommendations of Cherubini et al. (2011), considering a global warming potential of 0.18.

The life cycle costing included the cost of purchasing the stoves and that of charcoal depending on the context. The cost of repair was, however, not included since many households do not repair but rather replace the stoves once worn out. It is worthwhile to mention that in the case of wood-based fuels such as firewood and charcoal, the model presumptions spanned over a wide range of probable carbon footprints. The traditional energy pathways aimed at bringing out the worst possible case scenarios, whereas the improved pathways were determined to showcase the best possible outcomes of the wood-based energy pathways. This was as a result of incorporating the least efficient and the most efficient production and consumption technologies. The aim was to identify points of improvement along the wood-based fuel pathway for the best possible outcome.

4.4 Biogas Value Chain

Anaerobic decomposition of organic matter generates gaseous product known as biogas, which is essentially composed of methane (CH_4) 60-70% and carbon dioxide (CO_2) 30-40% (Jungbluth et al., 2007). Biogas digesters produce flammable gas and a by-product known as digestate (bio-fertiliser) through the microbial degradation of organic matter, such as freely accessible animal droppings, crop residue and waste generated from industrial and municipal processes, under oxygen free conditions (Cornejo & Wilkie, 2010). As such, it can be produced from nearly all kinds of organic matter in the waste stream. These wastes, in cases of inappropriate management, can lead to water and air pollution. However, by using waste products and animal dung, biogas can help in reducing these negative environmental impacts. Biogas production through anaerobic digestion is considered a very old technology which to date is still not fully exploited

(Ericsson et al., 2013). The choice of biogas for this research was centred on its likelihood to offer an alternative source of energy as a result of putting to use organic matter often considered as waste material that are readily available within the surrounding environment.

4.4.1 Feedstock Collection

This study considered the use of cow dung for biogas production since it is a readily available waste product from animal breeding in most rural households. The ecological burdens linked to the use of cow dung used for the generation of biogas are assigned to keeping of livestock and to the generation of biogas. Farmers practicing small-scale farming regularly gather the cow dung and use it as manure. Generation of biogas leads to multiple output including biogas and digestate. The digestate can be spread on the farms to enhance the fertility of the soils for increased crop productivity. As such, the study presumed that the adoption of cow dung for the purpose of generating biogas does not deny these small-scale farmers would be soil improvement functions of cow dung. In addition, some household use dry cow dung as a source of fuel. The use of cow dung for biogas production has the potential of providing better quality fuel which is not smoky and does not emit particulate matter. This, therefore, does not deprive households of its fuel provision.

The collection of cow dung is often done manually and, therefore, free of environmental loads. In addition, cow dung is usually collected within the homesteads and does not require transportation. As such, no environmental burdens are accounted for in this respect (Jungbluth et al., 2007). The life cycle costing included the cost of labour considering the hours used to collect the cow dung. In Kitui, a free range system of animal keeping was adopted. Fresh manure production per cow is estimated to range from 25 to 30 kg/head/day (Guo, 2010). Therefore, with an average of two cows per household, it was estimated that it took one hour to collect 60kg of cow dung. In Moshi, this scenario adopted the zero grazing system of animal keeping since it is a high potential area. Intensive animal husbandry is practiced especially on the southern slopes of Mount Kilimanjaro (Ulicky et al., 2013). Zero grazing units allow for accumulation of the cow dung in one place and, therefore, this study estimated that one required half an hour to collect an equivalent amount of cow dung. The cost of building a zero grazing unit was, however, not included in the life cycle cost analysis but instead, allocated fully to cattle keeping. Similarly, the cost of the equipment used was not included since their use is not exclusive to biogas production.

4.4.2 Feedstock Processing

The technologies selected for biogas production (Plate 4.11) include the plastic biogas digester adapted for Kitui Central and Vietnam Gardening Association (VACVINA) adapted for Moshi. The VACVINA biogas digester is a better form of the fixed dome. The daily loading rate of livestock waste for anaerobic digester at ambient temperatures ranges from 0.35 to 0.45 kg dry matter of waste or 3.5 to 4.5 kg fresh livestock waste for 1m^3 of digestion volume (Chinh et al., 2013). It is approximated that 32kg feedstock is needed to produce 1m^3 biogas (Afrane & Ntiamoah, 2011). The LCA included the emissions generated by the process of biogas production and methane loss of 1% (Afrane & Ntiamoah, 2011) due to methane leakage. Biogas generation results in two products, namely, biogas and digestate/slurry. The digestate or slurry is applied manually to the small scale farms but does not replace inorganic fertilisers since the small holder farmers in the study sites rarely use the inorganic fertilisers to improve soil fertility. The LCA, therefore, did not consider the displacement of inorganic fertilisers with the digestate. On the other hand, the LCC analysis of biogas production considered the price of installing the digester which included the installation costs in addition to labour used while loading the feedstock into the digester.

4.4.3 Transport

Biogas production is done at the site of its consumption. Based on this, the biogas value chain is excluded from the urban context analysis since its use is restricted to the rural areas.

Plate 4.11: Biogas digesters

4.4.4 Use/Consumption

The study applied a thermal efficiency of 55% (Afrane & Ntiamoah, 2011) for the biogas burner (Plate 4.12) with an estimated lifespan of 10 years.

Plate 4.12: Biogas burner

A fuel energy content of 17.71 MJ/kg for biogas (Shrestha, 2004; Afrane & Ntiamoah, 2011) was adopted by this study. The life cycle costing considered the purchasing price of the burner only.

4.5 Jatropha Oil Value Chain

The process of pressing dry *Jatropha curcas* seeds (commonly termed as jatropha seeds) (Plate 4.13) and filtering results in the production of a biofuel that is used for cooking in a biofuel stove. Jatropha plant is called "*mbono*" in the Swahili language. In

Africa, jatropha is thought to be among the most feasible raw material for the production of biofuel mainly because it easily adapts to semi-arid lands (Tomomatsu & Swallow, 2007; Shinoj et al., 2010) and, therefore, the potential to use degraded areas for its cultivation. Jatropha which is a shrub is known to be an energy crop with encouraging benefits, some of which are expansion of energy security and decreasing the emissions of greenhouse gases (Parawira, 2010). This study considered jatropha seeds from jatropha hedges only. Jatropha hedges emit less carbon dioxide (CO_2) compared to large jatropha plantations as documented by Feto (2011) in a study done in Ethiopia.

Plate 4.13: Jatropha seeds

Establishment of large plantations to satisfy the demand for jatropha oil would lead to land use change. This is due to replacement of agricultural and forest land, resulting in huge amounts of carbon emissions into the atmosphere, in addition to unfavourable social and environmental changes in the affected communities (Tomomatsu & Swallow, 2007;

Pohl, 2010; Feto, 2011). In addition, the study presumed that use of jatropha plant for demarcation of boundaries was a suitable source of seeds since they are not a source of competition with food crops for the agricultural land (Potner et al., 2014). Additionally, establishment of these hedges does not need application of herbicides and fertilisers, or use of irrigation water.

Restricting the investigation to jatropha hedges consequently eliminating the cultivation of jatropha on plots, was fundamental to control for the adverse impacts on food security. Furthermore, the maintenance of hedges is not as labour intensive compared to other processes along the jatropha oil pathway such as drying, husking and pressing of the jatropha seeds using a manual press. Accordingly, such inputs needed not to be considered in this study. The common oils and fuels from jatropha seeds include Straight Vegetable Oils (SVO) and biodiesel. This study, however, only focused on SVO fuel used for cooking. The modelling of the jatropha oil value chain was based on two scenarios considering the type of technology used for the feedstock processing (pressing of the oil). The first scenario considered the use of a manual jatopha oil press while the second scenario considered use of a diesel powered jatropha oil press.

4.5.1 Feedstock Collection

Collection of the jatropha seeds from hedges (Plate 4.14) is done manually, and therefore, no emissions were included. The life cycle costing included the labour cost of harvesting seeds while considering the hours spent on harvesting. It takes approximately three hours for one person to manually collect jatropha seeds (UN, 2007); which was used in this analysis

4.5.2 Feedstock Processing

Jatropha seeds are crushed to extract the oil. This can be extracted using hand held oil presses such as the ram press and mechanical presses. Jatropha oil processing is categorised as either jatropha oil manual press value chain or jatropha oil diesel press value chain. This is determined by the type of press used for oil extraction.

Plate 4.14: Jatropha hedge

Scenario 1: Jatropha Oil Manual Press Value Chain

This scenario adopted use of the manual press (Plate 4.15) for jatropha oil processing and is herein referred to as the jatropha oil manual press value chain. For pressing of small amounts of seeds ranging between 1-10kg seed/hr appropriate presses include the ram presses and expellers. Small scale hand held jatropha oil extractors such as the ram press have the potential to extract 1 litre of oil from every 5 to 5.5 kg seed. These presses are comparatively inefficient, leading to the extraction of only roughly 60% of the oil. However, when pressing large quantities of seeds such as above 10 kg/hr expellers should be used since the hand operated presses are not suitable anymore (FACT Foundation, 2010).

Plate 4.15*: *Manual jatropha oil press

Scenario 2: Jatropha Oil Diesel Press Value Chain

This scenario adopted use of the diesel powered jatropha oil press (Plate 4.16) for jatropha oil processing and is herein referred to as jatropha oil diesel press value chain. The diesel powered oil press was preferred over the electric oil press since a large majority of rural parts still lack electricity. Therefore, the assumption was that use of the diesel press would ensure a consistent supply of the jatropha oil. The diesel press is estimated to consume 1.5 litres of diesel per 70 kg bag of dry jatropha seeds (Sanga & Meena, 2008) or 10% calorific value of the oil produced (FACT Foundation, 2010). Engine driven presses have the capacity to extract between 75% and 80% of the obtainable oil thus producing one litre of jatropha oil from every 4 kg of dried seeds (Achten et al., 2008; Brittaine & Lutaladio, 2010). Dry jatropha seeds are estimated to have an of average of 34% oil content (Achten et al., 2008). Jatropha oil production is a multi-output process that leads to the production of the oil and seedcake. The substitutability of mineral fertiliser with seed cake is, however, not factored in since small scale famers hardly use these inorganic fertilisers. The assumption applied in this study is that it would displace cow dung which comes free of environmental load within the context of this study and, therefore, no displacement is necessary.

Plate 4.16: Diesel powered jatropha oil press

4.5.3 Transport

The oil is presumably transported using a motorbike which is the most common transport mode in the two sites.

4.5.4 Use/Consumption

The study applied a stove efficiency of 39.5% for the jatropha oil (biofuel) stove as seen in Plate 4.17. An energy content of 39.8MJ/kg assuming a stove lifespan of 25 years was applied in this study.

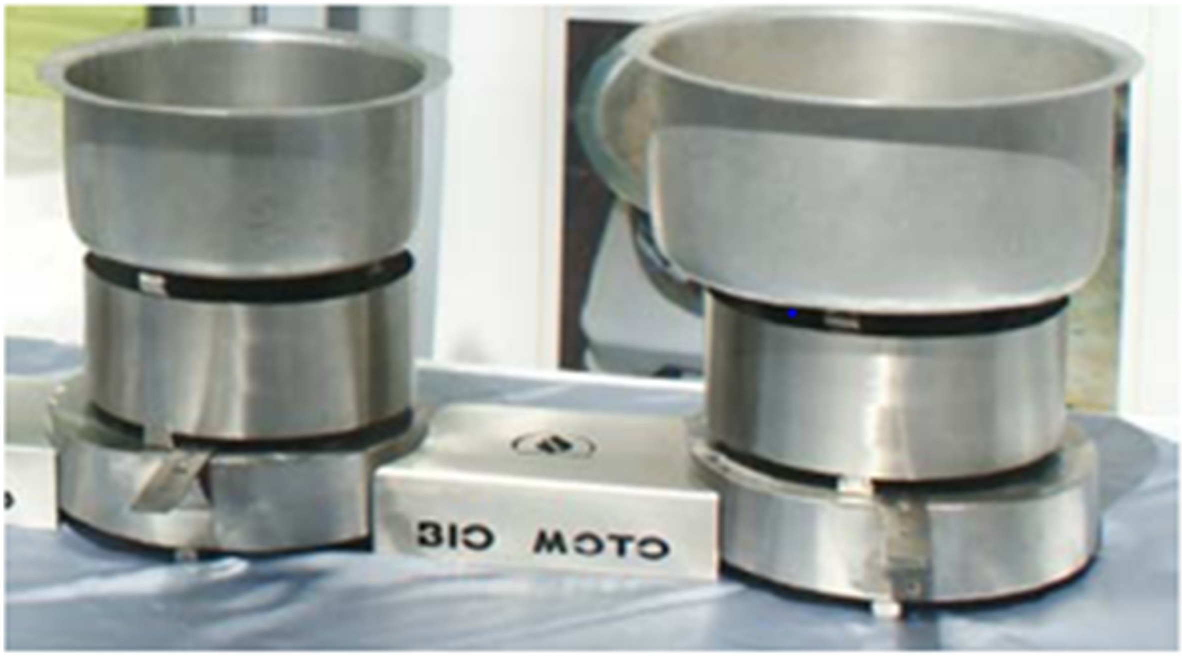

Plate 4.17: Jatropha oil stove

The LCC considered the cost of using the jatropha oil stove for cooking while taking into consideration its purchase price.

4.6 Crop Residue Briquettes Value Chain

Raw materials are compacted into different shapes and sizes of moulds known as briquettes (Plate 4.18). Briquettes have the potential to become a substitute fuel for households. Among the raw materials that have the possibility of being compacted into briquettes are crop residues with the aim of increasing the biomass energy options for households. However, it is important to note that crop residues have other competing uses such as fodder used for feeding livestock, mulching material to improve retention of water in the soil, in addition to being converted to compost manure used in the farms to improve soil fertility. This study, however, assumed that the supply of crop residues was sufficient and as a result their use for provision of fuel would not deny households of their other functions.

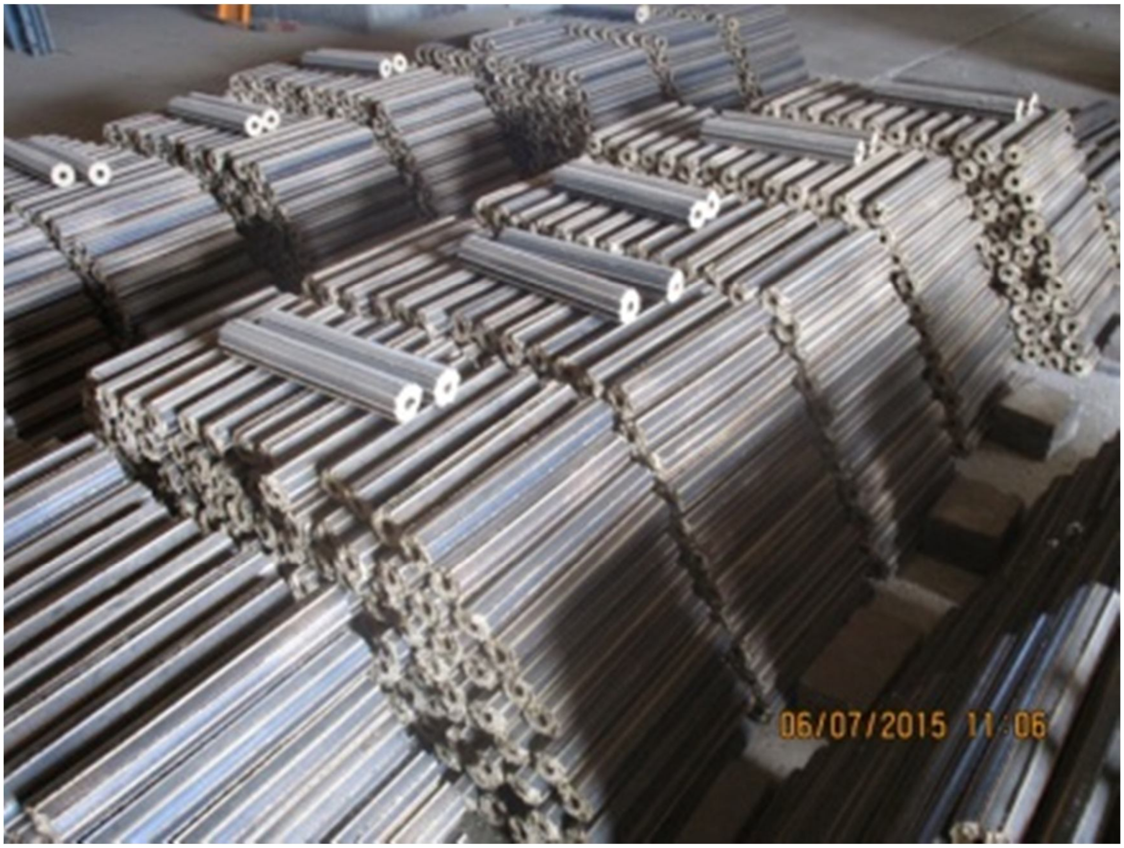
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Plate 4.18: Rice husk briquettes

The ecological burdens associated to crop residues used for making briquettes were assigned to farming of the specific crop and not to the production of briquettes because they were treated as waste products. Again, the crop residue value chain was modelled in two scenarios depending on the type of press used: manual briquette press and the diesel powered briquette press.

4.6.1 Feedstock Collection

Maize cobs and rice husks were used as the raw material for briquette making in Kitui and Moshi, respectively. This was mainly attributed to the local availability of these raw materials for making briquettes, which were also considered as waste material. In Kitui, maize stalks are used for animal fodder or integrated into the soil as manure, while maize cobs are used directly as a fuel for cooking. As such, the maize cobs were preferred to maize stalks for producing briquettes. In Moshi, rice husks are usually burnt in the open fields after harvesting and do not serve for other uses. Since there is no mechanisation involved in the collection of crop residues in the small holder farms, the study applied manual collection while modelling feedstock collection. On the other hand, the life cycle costing considered the labour hours used for feedstock collection. In this model, the study estimated that it took one person one hour to collect 10kg of crop residues from the fields/farms.

4.6.2 Feedstock processing

Scenario1: Briquette Manual Press Value Chain

Briquette making using the manual briquette press (Plate 4.19), herein referred to as the crop residue briquette manual press value chain, necessitates the use of a binder material (Ngusale et al., 2014). The binder material is used to hold together the raw material used to make the briquettes. This LCA study adopted the use of waste paper such as old newspapers as encountered during the field visit in Kitui. The usage of starch, which primarily comes from food crops, as binder material was avoided in this study so as to eliminate conflict between energy and food needs.

Plate 4.19: Manual briquette presses

Scenario 2: Briquette Diesel Press Value Chain

Briquette making using diesel powered press (Plate 4.20), herein referred to as the crop residue briquette diesel press value chain, does not necessitate a binding material since the procedure produces high temperatures sufficient for binding the crop residue (Ngusale et al., 2014). The LCA calculations for both the manual and diesel powered briquette presses were based on press efficiency (briquette production) of 100% (Practical Action data) and an estimated lifespan of 10 years when operating eight hours per day. The cost per megajoule analysis included the cost of the presses. Labour hours were also factored in considering a production rate of 12kg/hour and 100kg/hour for the manual and diesel powered briquette presses respectively (Ngusale et al., 2014).

Plate 4.20: Diesel powered briquette press

4.6.3 Transport

Transportation of the briquettes using a motorbike was adopted since it is the most common mode of transport in the two study sites.

4.6.4 Use/Consumption

The cooking device selected for this study was the briquette stove (Plate 4.21). The study applied a thermal efficiency of 32% for the briquette stove; similar to that of the Kenya Ceramic Jiko (Jetter et al., 2012) due to the similarity in stove design.

Plate 4.21: Briquette stove

The briquette stove, just like the KCJ, has a single ceramic liner. A lifespan of three years was also adopted for this stove. Adoption of the KCJ properties by the briquette stove was due to the fact that no literature was found referring to the efficiency of this stove. This efficiency has been used to model the fuel consumption and consequently the carbon footprint of the stove. Fuel energy content of 17.65 MJ/kg and 18.15 MJ/kg was applied for maize cob and rice husk briquettes, respectively (Oladeji, 2010). The life cycle cost analysis included the cost of the briquette stove and that of the briquettes.

CHAPTER FIVE

CARBON FOOTPRINTS OF ALTERNATIVE BIOMASS ENERGY VALUE CHAINS FOR COOKING

5.1 Introduction

This chapter presents the carbon footprints as one of the ecological effects of a selection of biomass energy pathways. A comparison is made among these selected biomass energy value chains with the aim of providing policy makers and stakeholders with the necessary information for biomass energy policy development based on their carbon footprints. The results are presented according to the lifecycle pathways i.e. feedstock collection, processing, transport (only for urban context) and use. The chapter goes ahead to give an overview of the carbon footprints of the value chains.

5.2 Carbon Footprints of Biomass Energy Value Chains

5.2.1 Feedstock Collection

Harvesting of wood has a considerable contribution to the carbon footprints of firewood and charcoal pathways, respectively. The unsustainable wood extraction methods that characterise the traditional firewood and charcoal pathways results in the largest amounts of carbon footprints: 0.35 CO_2eq/MJ and 0.94 CO_2eq/MJ, respectively. Wood extraction methods that are deemed sustainable shrink the carbon footprint of wood extraction of the improved firewood pathway to 0.03 CO_2eq/MJ (Kitui) and 0.02 CO_2eq/MJ (Moshi). However, this carbon footprint remains larger than that of the non-wood-based energy pathways. Similarly, the improved charcoal pathway has a higher carbon footprint of 0.08 CO_2eq in Kitui than in Moshi where it is 0.06 CO_2eq/MJ (Okoko et al., 2017).

Interviews conducted in the two research sites showed that charcoal producers preferred making charcoal using the indigenous trees that they stated yielded dense, slow-burning charcoal (locally referred to as “heavy charcoal”). These tree species take a longer time to reach maturity and are, therefore, extremely susceptible to overexploitation (Girard, 2002). It is worthwhile to point out that the re-establishment of these trees in the two research sites largely depends on natural regeneration and, therefore, their non-stop extraction does not permit time for this re-establishment. The demand for wood for provision of firewood especially for the rural communities and for charcoal to be supplied in the urban surroundings is creating pressure on the forests. This is, therefore, threatening the existence of the few remaining forests more so if adequate measures of protecting these forests are not put in place. The current wood extraction methods according to the results presented by this research indicates the possibilities for overexploitation of forest resources, subsequently leading to an upsurge in the quantity of carbon dioxide emitted in the atmosphere (MacCarty et al., 2008). Only sustainable wood extraction methods allow the growing biomass to re-absorb the carbon dioxide emitted in the process of burning wood.

The results indicate that the feedstock collection phase of the biogas, jatropha oil and crop residue briquette pathways are free of any ecological load. This is because the ecological loads associated with gathering of cow dung, which is the preferred raw material for biogas generation, are assigned to livestock farming. Likewise, the environmental load linked to rice and maize farming is assigned to their respective agricultural production systems. Similarly, feedstock collection phase of the jatropha oil value chain is considered free of environmental burdens since the cultivation of jatropha hedges does not need use of herbicides, fertilizers, or water for irrigation purposes. In addition, these hedges do not compete with food crops for land put under agriculture, therefore, making their collection free of any environmental load. Additionally, collection of cow dung, crop residues and jatropha seeds does not apply any mechanisation and, therefore, free of emissions.

5.2.2 Feedstock Processing

Feedstock processing is not a requirement for firewood energy pathways because the wood is used as it is after being extracted manually. The unimproved charcoal pathway comprises processing of the extracted wood using a basic earth kiln mound that indicates a carbon footprint of 0.50 CO_2eq/MJ. By comparison this carbon footprint is 24% (0.38 CO_2eq/MJ) greater than that of the improved basic earth kiln in Kitui. Similarly, it is greater by 45% than that of an improved basic earth kiln in Moshi (Okoko et al., 2017). The difference in the carbon footprints as indicated by the results in the two research sites is as a result of the varying thermal efficiency levels of the enhanced charcoal stoves adopted for each research site, therefore, differentiating the contribution to the overall carbon footprints of the earlier processes. .

In the rural settings, generation of biogas as a fuel for cooking while using the plastic digester has a carbon footprint of 7.8E-07 CO_2eq/MJ. The carbon footprint of biogas generation using the VACVINA biogas digester is 9.83E-07CO_2eq/MJ (Okoko et al 2017). The anaerobic digestion of cow dung, the main feedstock in this study, reduces the methane production potential when compared to undigested manure left in the fields (Garfí et al., 2012; Nzila et al., 2012). Ensuring proper handling of animal dung helps in avoiding release of methane gas into the atmosphere because the organic matter is decomposed in a controlled environment within the biogas digester whereby collection of the resultant gas is made possible (Yu et al., 2008).

The results indicate that production of jatropha oil using the manual press in both the urban and rural settings has a carbon footprint of 1.3E-04 CO_2eq/MJ, which contributes only 2% to the overall carbon footprint of the jatropah oil manual value chain (Okoko et al., 2017). Jatropha oil extraction using the manual press has a lower carbon footprint than that of making briquettes using a manual press by 79% (6.3E-04 kgCO_2eq/MJ). However, extraction of jatropha oil using the diesel powered press escalates this carbon footprint by 99%. Jatropha oil production using the diesel powered press has a contribution of 96% and 87% to the carbon footprints of the jatropha oil diesel value chain in the rural and urban contexts, respectively. The difference in the carbon footprint of the jatropha oil manual and diesel press is attributed to the use of diesel for powering the jatropha oil press.

Crop residue briquette production phase using the manual briquette press has a carbon footprint of 6.316E-04 kgCO_2eq/MJ contributing 3% and 2% of the carbon footprint along its value chain in the rural and urban contexts, respectively. On the other hand briquette production phase using the diesel powered briquette press leads to a carbon footprint of 6.40E-02 kgCO_2eq/MJ contributing 76% and 71% of the carbon footprint along the crop residue diesel value chain in the rural and urban contexts, respectively. The use of the diesel powered briquette press increases the carbon footprint of briquette production by up to 99%. The difference can be attributed to use of diesel in the briquetting process when the diesel powered press is used.

5.2.3 Transportation

In most rural settings, firewood is commonly transported using bicycles to the nearby urban areas. The effect of this means of transportation is significantly lesser than that of motorcycles. However, the general outlook of biomass energy transportation is of less significance due to the insignificant ecological impact compared to the other phases of the biomass energy pathways. Firewood and charcoal transport contributes between 1% and 2% of the overall carbon footprints along their respective value chains. Transportation of jatropha oil and crop residue briquettes has a carbon footprint of 0.0024 kgCO_2eq/MJ and 0.006 kgCO_2eq/MJ, which is a contribution of 30% and 23% along the jatropha oil and crop residue briquette manual value chains, respectively. On the other hand, transportation of these biomass fuels along the diesel powered value chains has a contribution of 8% and 7%, respectively, with similar carbon footprints.

5.2.4 Consumption

The results indicate that emissions due to firewood use vary depending on the cooking technology. The results also indicate highest emissions from the three stones fireplace in both the rural and urban settings. Use of better efficiency stoves decrease the carbon footprint of firewood burning from 0.9 CO_2eq/MJ, to 0.15 CO_2eq/MJ (*maendeleo*), 0.11 CO_2eq/MJ (*kuni-chache*), 0.09 CO_2eq/MJ (rocket, *envirofit*) and 0.07 CO_2eq/MJ (*okoa*) where regrowth of trees is assumed. Combustion of dead wood further reduces this carbon footprint to 0.04 CO_2eq/MJ (*maendeleo*), 0.03 CO_2eq/MJ (*kuni-chache,* rocket, *envirofit*) and 0.02 CO_2eq/MJ (*okoa*) and is the sole contributor to the carbon footprints of firewood. Change in climate is as a result of emission of methane, carbon monoxide and particulate matter (MacCarty et al., 2008).

Improved efficiency of the firewood stoves reduces the wood consumption, consequently reducing the amount of greenhouse gas emissions into the environment.

Low efficiency firewood stoves such as the 3 stones fireplace places a huge demand on wood compared to the improved wood stoves to deliver an equivalent amount of energy. For instance, the three-stones fireplaces requires up to 0.44 kg/MJ compared to 0.18 kg/MJ and 0.13 kg/MJ required by *envirofit* and *okoa* wood stoves, respectively.

Similarly, the use of a better efficiency charcoal stove shrinks the carbon footprint of charcoal burning from 0.70 CO_2eq/MJ to 0.11CO_2eq/MJ in the case of Kenya Ceramic Jiko used in Kitui and 0.08 CO_2eq/MJ in the case of *sazawa* charcoal stove used in Moshi. Burning of jatropha oil in a jatropha oil stove leads to a carbon footprint of only 0.001 CO_2eq/MJ. The research clearly indicates that enhanced cooking devices characterised by high efficiencies, such as the ones presented in the previous section, portray significant ecological benefits such as significant decline in the wood consumption rate and lowering of the demand for wood resources. Additionally, adoption of plant oils to provide cooking energy needs of rural and urban households in the place of solid biomass fuels indicate additional benefits such as health benefits as a result of the significant reduction in carbon monoxide and micro-particles releases.

Carbon footprints of biogas combustion in the rural setting are 83% lower compared to combusting firewood in unimproved firewood cooking devices. However, it is 80% greater than the combustion of crop residue briquettes. The carbon footprint of biogas combustion is reported to be 78% smaller when compared to combustion of charcoal using the unimproved charcoal cooking device. Biogas combustion reduces the amount of methane released into the atmosphere by converting it into carbon dioxide which is released in to the atmosphere. Methane gas is reported to be 21 times more destructive than carbon dioxide (Garfí et al., 2012; Nzila et al., 2012). In addition, the combustion of biogas emits less greenhouse gas compared to traditional biomass energy form such as firewood, which is the most frequently used fuel by households in the rural areas (Garfí et al., 2012). The general output of biogas stoves, however, is influenced by the sufficiency of the primary air inlet in the process of combustion (Sasse et al., 1991). If very minimal primary air is added to the mixture, the biogas does not combust completely and, therefore, some of it leaks out. Such escape of methane gas (CH_4) from biogas systems result in increased global warming potential, since methane is a very toxic greenhouse gas (Afrane & Ntiamoah, 2011). This provides an insight into an aspect of the biogas burner that can be improved for better environmental performance.

Combustion of jatropha oil has a carbon footprint of 0.001 kgCO_2eq/MJ contributing 88% and 28% to the carbon footprints of the jatropha oil manual value chain in the rural and urban contexts, respectively. On the other hand, it contributes 4% to the carbon footprint of the diesel value chain in the rural and urban context respectively. The low greenhouse gas emission by the stove is attributed to a high stove efficiency and lower fuel consumption of 0.06 kg/MJ. An additional benefit associated with use of the jatropha oil stove is its potential to reduce exposure of the cooks to particulate matter and carbon monoxide gas (Huboyo et al., 2013). However, according to UN (2007) and Huboyo et al. (2013), there is the need for some modifications on the jatropha oil cook stoves. Huboyo et al. (2013), in their study state that as a way of enhancing the performance of jatropha oil stove, it is vital that the refuelling process is improved to increase the oil holding capacity since the current stove configuration does not allow addition of fuel while cooking. This observation, therefore, provides a lead to the non-adoption/low adoption of jatropha oil as a cooking fuel in addition to inaccessibility and unavailability and of the technology.

Burning of crop residue briquettes compared to the burning of firewood in a traditional stove in both rural and urban settings decrease the carbon footprints by 97%. Briquettes made from raw materials that have no additional economic use such as coffee husks, maize residues, bagasse, rice husks and sawdust, provide fuel considered sustainable. These briquettes have the potential to substitute unsustainable fuels such as traditional firewood and charcoal (GVEP International, 2010).

5.2.5 Overall Carbon Footprint of Biomass Energy Value Chains

The traditional charcoal energy pathway indicates the chain has the highest carbon footprint of 2.15 CO_2eq/MJ in both Kitui and Moshi, while that of the jatropha oil value chain using a manual press being the lowest at 0.001 CO_2eq/MJ.

Firewood Value Chain

Sustainable extraction of firewood coupled with use of better efficiency stoves for cooking offer the potential to significantly shrink the carbon footprint of firewood, from 1.22 CO_2eq/MJ in unimproved firewood value chains to 0.09CO_2eq/MJ (regrowth) and further to 0.03CO_2eq/MJ (dead wood) in the rural (Figure 5.1) and urban contexts (Figure 5.2) of Kitui and Moshi. In the two figures, improved value chains where regrowth is considered is denoted with "R" while that with dead wood is denoted with "D". An additional benefit of embracing the improved firewood pathway is due to its ability to decrease the demand for wood resources by up to 57% in Kitui and 69% in Moshi when compared to the traditional firewood pathway. This is as a result of coupling improved stoves, improved kiln and replanting of trees when harvested.

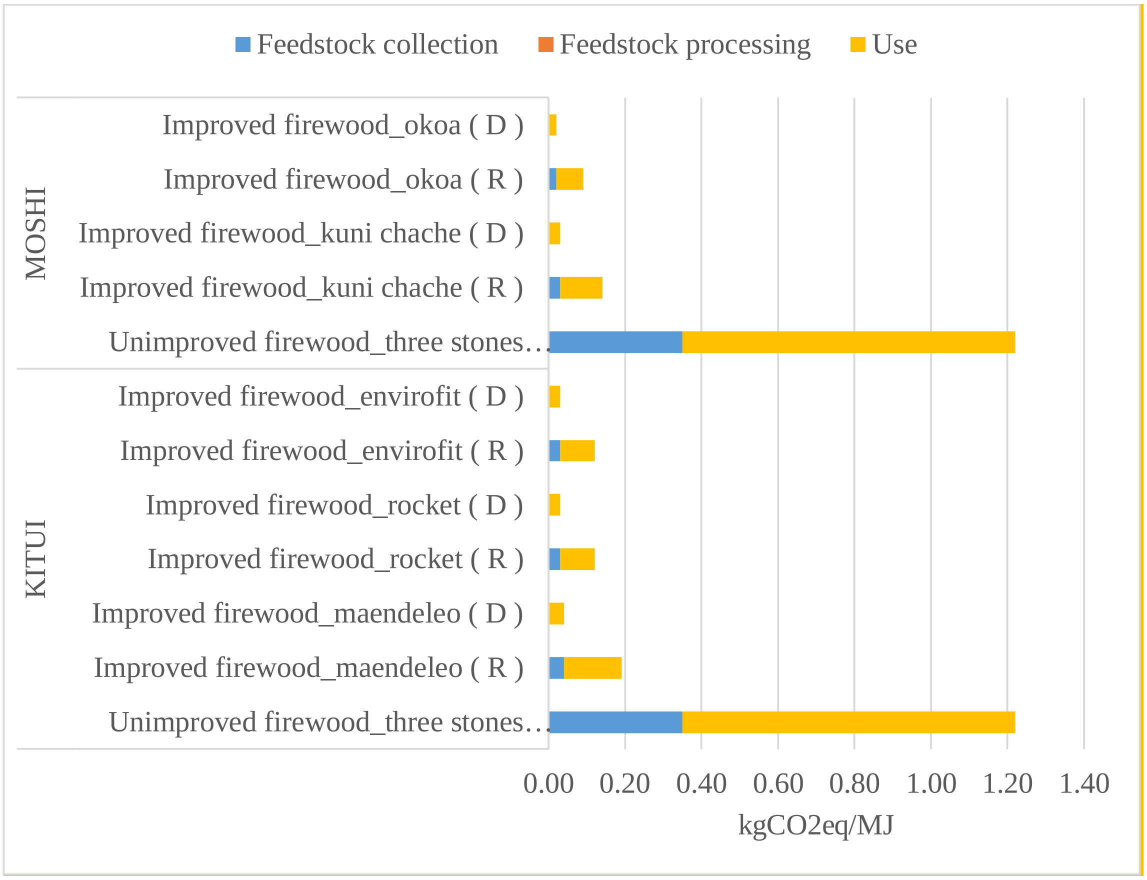

Figure 5.1: Carbon footprints (kgCO_2eq/MJ) firewood value chains in rural context

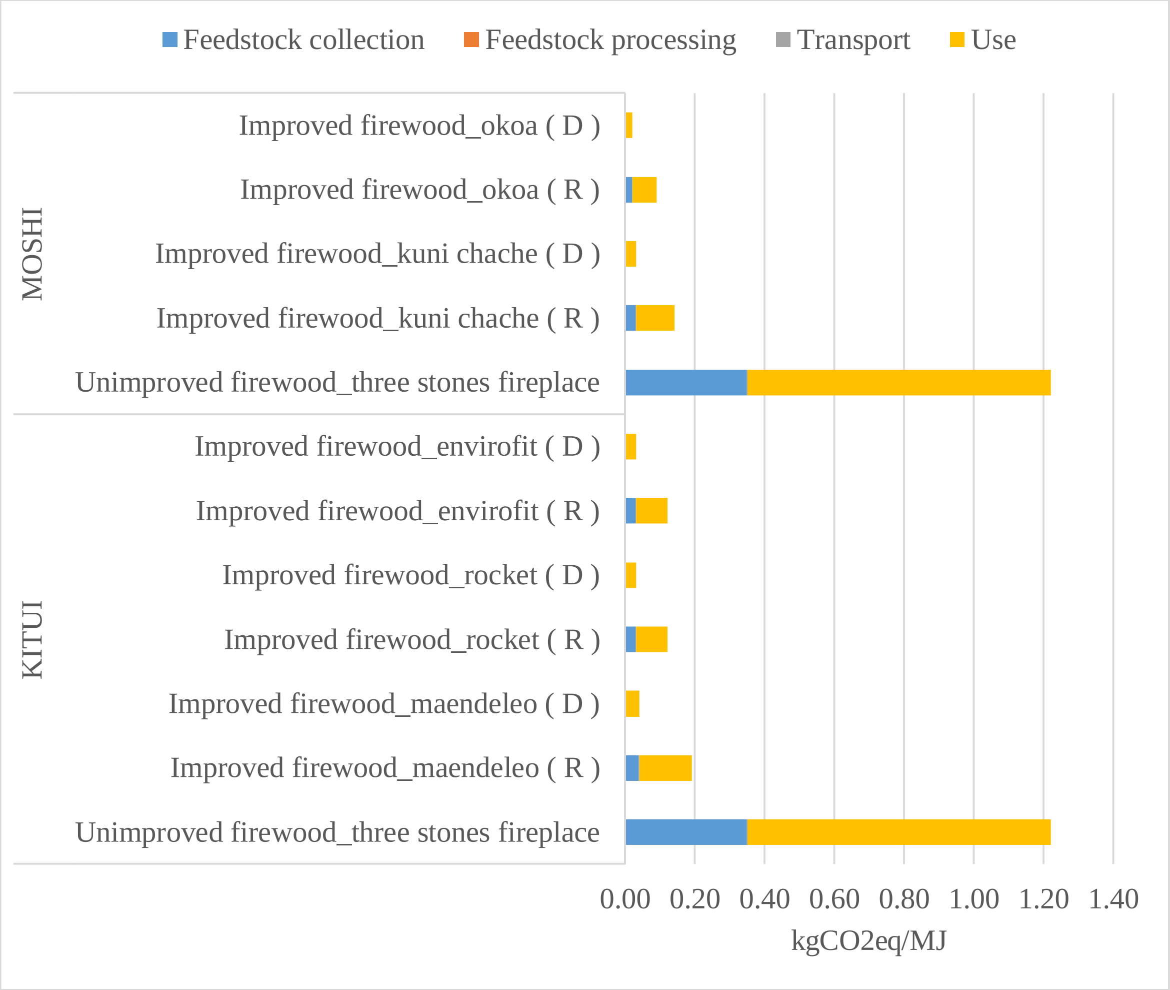

Figure 5.2: Carbon footprints (kgCO$_2$eq/MJ) firewood value chains in urban contexts

Unsustainable harvesting practices of forest products have the potential to lead to over-exploitation of forest resources. This would lead to an increase in the amount of carbon dioxide released into the atmosphere (MacCarty et al., 2008). If biomass resource is not extracted in an ecologically viable manner the carbon dioxide emitted during combustion will lead to an accumulation of carbon dioxide in the atmosphere (Bailis et al., 2003; MacCarty et al., 2008). However, in the event that the biomass resource is extracted in an ecologically viable manner, the carbon dioxide released during burning is ideally sequestered by the growing biomass which this study considers biogenic.

Initiatives that support parallel planting and harvesting of trees, harvesting of branches for purposes of firewood should, therefore, be encouraged in an effort to reduce their carbon footprints while mitigating the impacts of climate change. The benefits of climate change mitigation due to reduction in carbon footprints are further achieved by encouraging collection and combustion of dead wood (Figure 5.3). A report by World Bank (2011b), states that when using open fires and primitive stoves, the amount of fuel required for cooking annually could be approximately two tonnes for each family. Firewood consumption rate by a technology consequently possess a direct impact on the amount of greenhouse gas emissions released into the atmosphere.

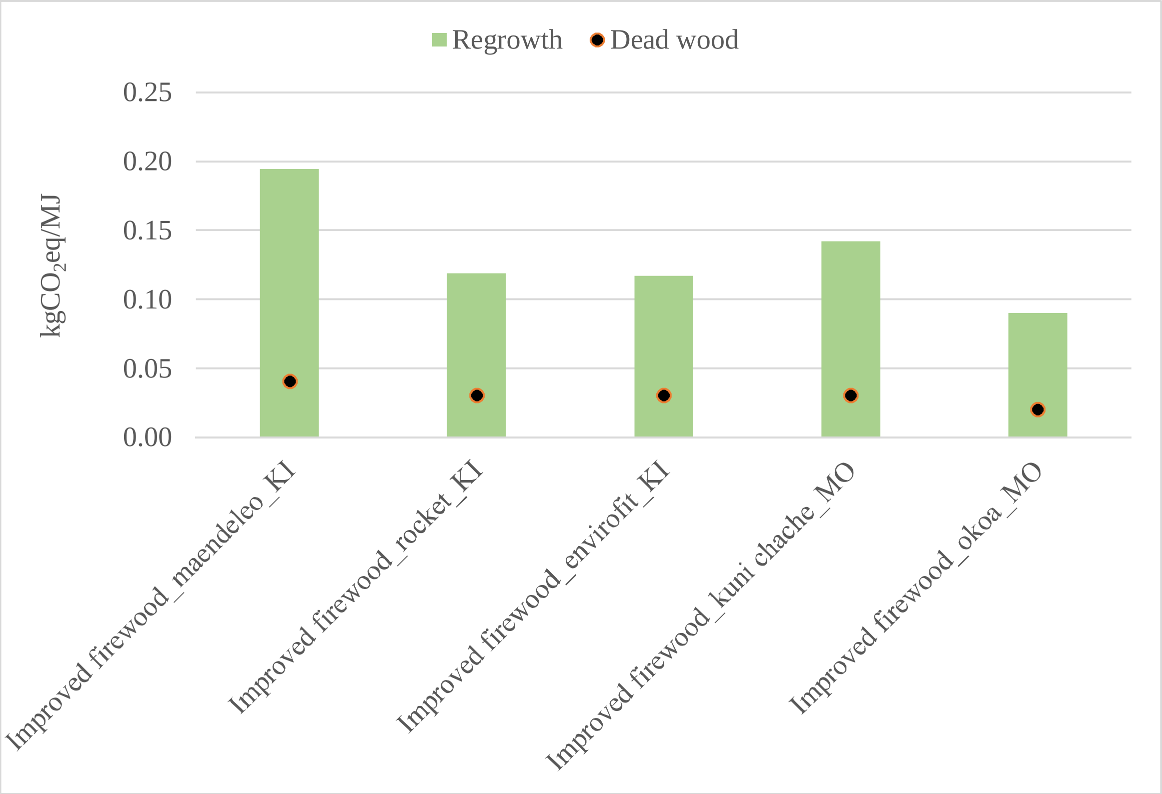

Figure 5.3: Carbon footprints (kgCO2eq/MJ) of improved firewood value chains in Kitui (KI) and Moshi (MO)

It is, therefore, important that efforts aimed at reducing greenhouse gas emissions by household biomass energy consider sustainable harvesting of firewood in addition to improvement in cook stove efficiency. The traditional use of biomass for cooking such as the three stones fireplace brings with it several negative health and social outcomes.

These include acute respiratory problems due to indoor air pollution. In addition, firewood collection is time consuming and physically demanding and affects women disproportionately (World Bank, 2011b; International Energy Agency, 2014). Its use has also been associated with environmental degradation, especially where trees are harvested unsustainably. Jetter & Kariher (2009) document lower pollutant emission by their rocket stove (improved firewood stove) model compared to the three stones fireplace just as in the current study. However, they recommend improvement of the combustion chamber so as to further improve its performance. They state that with the current thermal mass of the ceramic chamber, the stove takes a longer time to boil from a cold start. According to World Bank (2011b), better quality cook stoves are required for the purpose of air quality improvement, increasing the fuel efficiency and obtaining stove approval in the long run.

Efforts have in the recent past been put towards commercialisation and enhancing adoption of improved firewood cook stoves in Kenya and Tanzania. Despite these efforts by different stakeholders, the adoption of improved cook stoves remains very low. A study by Mutea (2015) in Kitui Central cites that the adoption rate of the *maendeleo*, rocket and e*nvirofit* stoves by the rural households who largely depend on firewood is 22%, 12% and 4%, respectively. This is despite their better environmental performance based on their potential to reduce carbon footprints of firewood compared to the three stones fireplace.

Charcoal Value Chain

In Kitui, the improved charcoal pathways leads to a reduction in the carbon footprint of charcoal by about 74% in the urban and rural settings compared to the traditional charcoal. Similarly, an 81% reduction in the carbon footprints of charcoal are realised in Moshi when compared to the traditional charcoal (Figure 5.4 and 5.4). Furthermore, the demand on wood resources is seen to decrease substantially by up to 54% in Kitui and 67% in Moshi where the improved charcoal pathway is examined. For every MJ of heat delivered to cooking pot, the improved charcoal value chain utilises 0.5kg of wood compared to 1.19kg wood demanded by the unimproved charcoal value chain. In addition, sustainable wood harvesting has the potential to reduce the carbon footprints of wood harvesting by up to 92% when compared to the unimproved charcoal value chain.

Figures 5.4 and 5.5 also show that for the improved charcoal pathways, the carbon footprint of processing the feedstock phase does not decrease significantly, as compared to the collection of feedstock, and the use phases. Feedstock collection and use phases indicate great potential for their improvement. This clearly indicates that for the charcoal path to experience any meaningful gains in terms of the environmental performance, a lot of effort must be put in these two phases. The carbon footprint of transportation phase is, however, quite insignificant in the urban setting in comparison to the other phases. Use of improved basic earth kiln compared to the basic earth kiln reduces the carbon footprints of the charcoal value chain by 24%. This can be attributed to its improved wood conversion efficiency, which ultimately reduces the amount of wood required to make an equal amount of charcoal as the basic earth kiln.

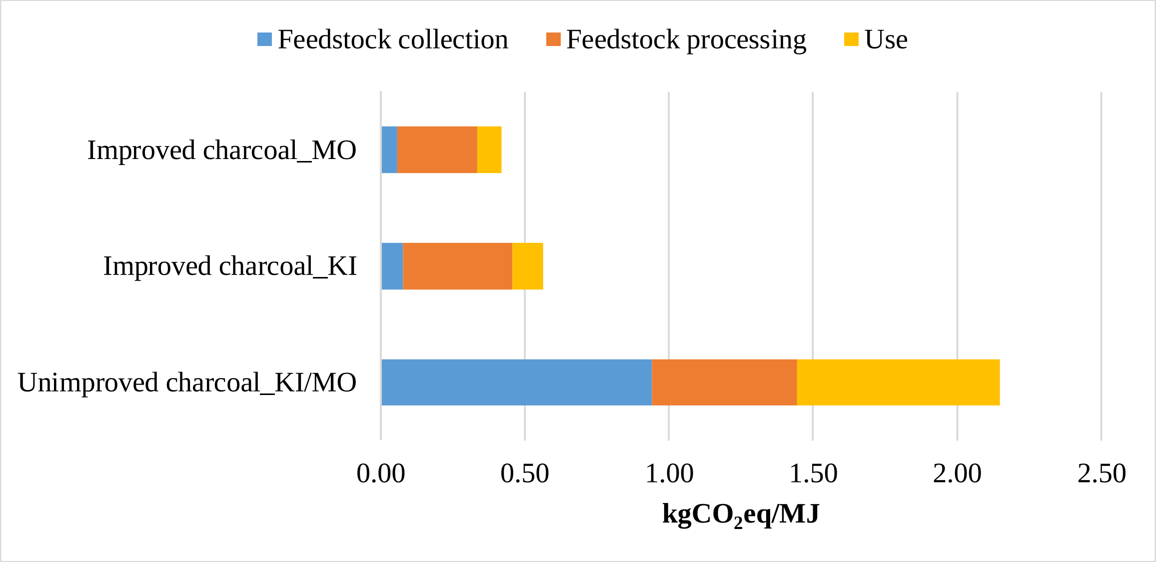

Figure 5.4: Carbon footprints (kgCO_2eq/MJ) charcoal value chains in rural contexts

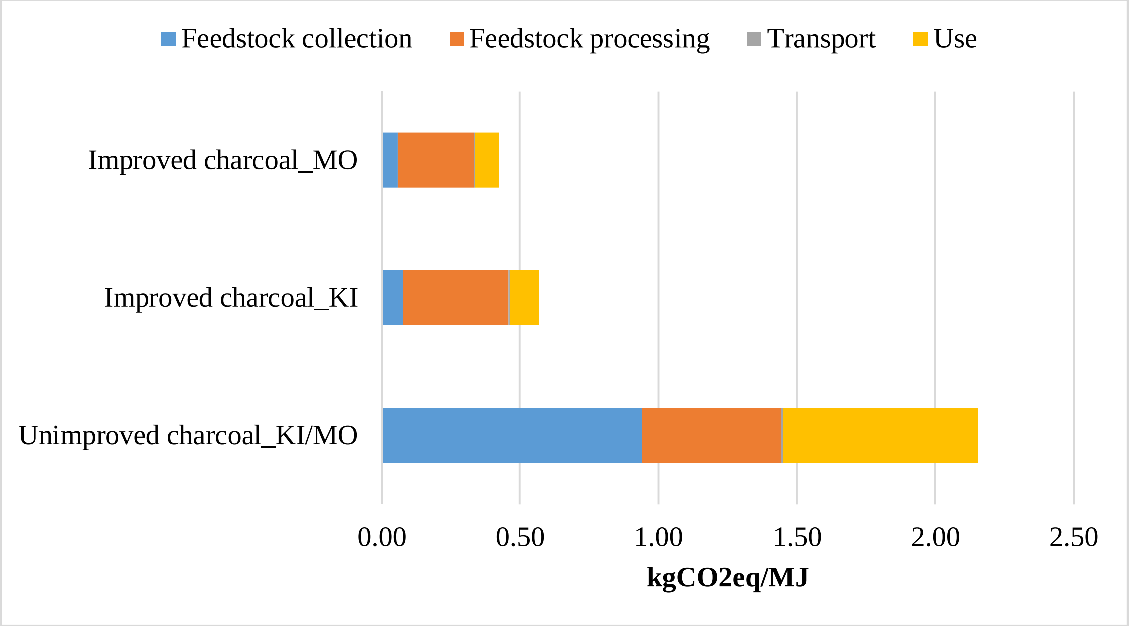

Figure 5.5: Carbon footprints (kgCO$_2$eq/MJ) of charcoal value chains in urban contexts

These results indicate that the carbon footprint of the unimproved charcoal value chain is 42% higher than that of the three stones fireplace. Similarly, the carbon footprint of the improved charcoal value chain in Kitui is 79% greater than that of the improved firewood value chain (*envirofit*). These findings support a study done in Uganda by Ekeh et al. (2014) which concludes that the primary use of charcoal as fuel for cooking will result to an increase in emission of greenhouse gases and increase in forest degradation in the long run. The study goes ahead to state that this trend in greenhouse gas emission and deforestation can only be mitigated by developing structures that warrant the sustainability of raw materials used for making charcoal. Ensuring the availability of alternative low-cost cooking devices is, additionally, important for mitigating greenhouse gas emission and deforestation. The shift from using firewood to charcoal for cooking is, therefore, expected to escalate the rate of degradation of the environment. The potential to mitigate carbon footprint by different biomass energy pathways brings forth opportunities for utilising carbon finance in a bid to help cut the prices to the poor households to enable them access energy that is considered clean and efficient for provision of their daily energy needs (UNDP and WHO, 2009).

Alternative Biomass Energy Value Chains

Emission of methane gas considerably results to a high carbon footprint of the biogas energy pathway. The results presented in Figure 5.6 indicate that the carbon footprint of the biogas value chain is 0.15kgCO_2eq/MJ. This outcome indicates that biogas is the least appropriate amongst the substitute biomass energy pathways in the research sites. The level of organic matter decomposition and the holding period of this organic matter in the biogas digester plays a key role in the efforts aimed at reducing the amount of methane released into the atmosphere. As such the higher the holding time, the lower the amount of methane is emitted. Technical faults between the biogas digester and the biogas burner causing leakages may result in further methane emissions.

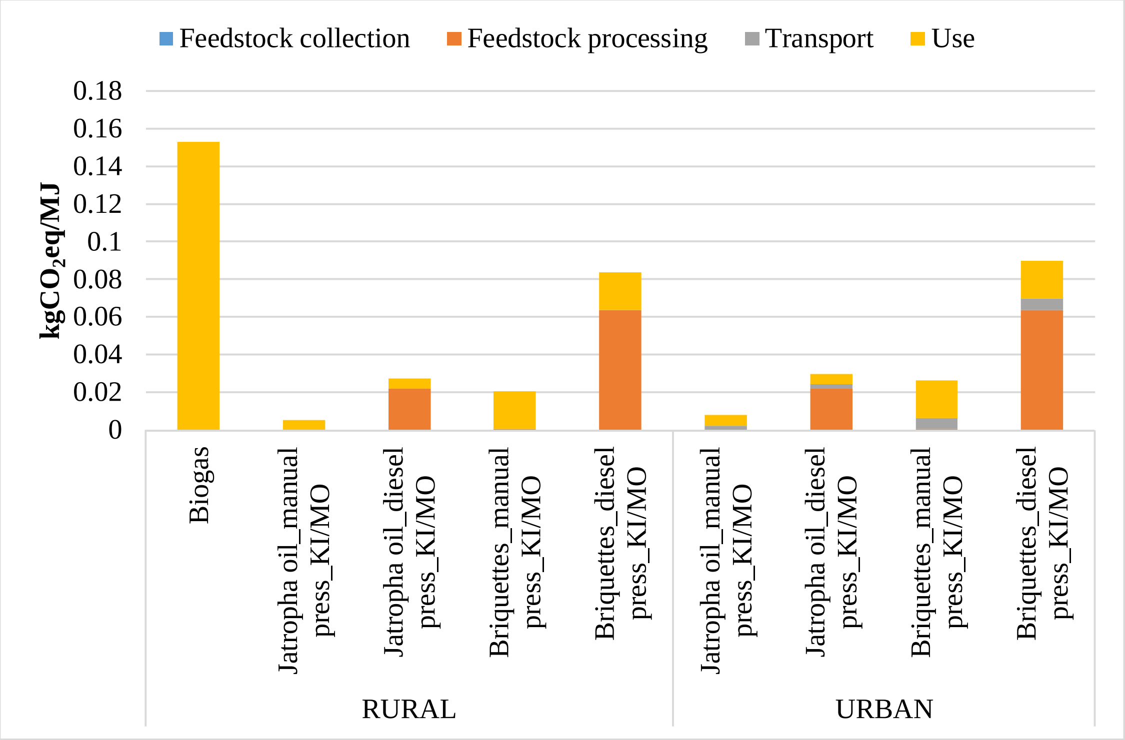

Figure 5.6: Carbon footprints of alternative biomass energy value chains for rural and urban contexts

Using the manual press for extracting jatropha oil indicates significant potential for decreasing the carbon footprints in Kitui and Moshi (Figure 5.6). Nevertheless, the ecological benefits obtainable from this pathway could be narrow as a result of the trivial quantities of jatropha seeds that can be harvested from jatropha hedges. As to whether this alternative can offer adequate raw material for the extraction of jatropha oil is yet to be established in lieu of the fact that oil extraction from jatropha hedges is the only way of avoiding competition for land with food crops. It is further debated that households would have to substantially increase the length of jatropha hedges if jatropha oil is to be thought as a suitable alternative to paraffin and wood (Ehrensperger et al., 2012). This could eventually not be practical, in addition to the intensive labour needed to gather the seeds from the extensive hedges, therefore, making it unaffordable.

This study concurs with Brittaine & Lutaladio (2010) who state that adoption of plant oil instead of traditional biomass fuels presents advantages. These advantages as stated by Brittaine & Lutaladio (2010) include health advantages as a result of reduced inhalation of smoke, ecological benefits such as energy security, preventing loss of forest cover and reduced greenhouse gas emission. Pohl (2010), in projected that biofuels would reduce carbon emissions by up to 66-68% and help save the climate compared to emissions from traditional diesel. Despite the fact that jatropha value chain may not provide a solution to all the challenges associated with energy in emerging countries, it is seen to possess the characteristics of biofuels with the potential to lead to viable agriculture and improved income (FACT Foundation, 2010).

GVEP International (2010), states that briquette made from raw materials, which would alternatively be considered as wastes offer a viable substitute for wood-based fuels such as firewood and charcoal. The bearing of enlarged briquette making and utilisation on ecological sustainability is reliant on the type feedstock and kind of fuel replaced. Briquettes made from agricultural residues will poses greater advantages over the fuel it replaces. For instance, the making of briquettes to replace charcoal would not necessarily result to adverse impacts such as forest degradation. However, obstacles to their adoption would have to be dealt with for the realisation of national benefits (GVEP International, 2010). World Bank (2011a), in their report, state that with improved fuels coupled with cook stoves with better efficiency have the potential to reduce emissions. The results presented in Figure 5.6 present an opportunity for the development of alternative biomass energy value chains necessary to bridge the energy gap especially for the rural and urban poor. This study, therefore, considers biogas, jatropha oil and briquettes as better biomass fuels with the potential to provide alternative sources of biomass energy.

5.3 Summary

The comparison of the carbon footprints of the selected biomass energy pathways as presented by this study shows that switching from firewood to charcoal value chain in the efforts to provide cooking energy for households will further aggravate the already destroyed ecosystems. Nevertheless, the firewood value chains need to be further improved by enhancing the uptake and adoption of improved cook stoves and reducing the reliance on the traditional firewood value chain so as to reduce the demand on wood resources.

Among the selected biomass energy value chains, jatropha oil value chains as presented in this study present the greatest potential for mitigating carbon footprint. From the results presented in this study, extraction of jatropha oil using the manual press presents the least carbon footprint thus greatest potential for mitigating greenhouse gas emissions. The jatropha oil manual press value chain when compared to the traditional charcoal value chain indicates a potential for reducing the carbon footprint by up to 99.6%.

Despite the fact that solutions like substituting unimproved cooks stoves with better biomass cook stoves or moving to the use of LPG or other modern energy sources are straight forward, there is an indication that the reliance on biomass energy in the coming ages by households will continue. The main motivation being that gas or LPG is affordable only to those with higher incomes (World Bank, 2011b).

This study concludes that alternative biomass energy such as biogas from cow dung, jatropha oil from hedges and briquettes from crop residues have the potential to reduce the carbon footprints substantially while still providing the needed energy for cooking.

CHAPTER SIX

LIFE CYCLE COSTS OF ALTERNATIVE BIOMASS ENERGY VALUE CHAINS FOR COOKING

6.1 Introduction

This chapter presents the life cycle costs of the selected biomass energy value chains. The chapter discusses the life cycle costs of biomass energy value chains by presenting the life cycle costs per megajoule of energy i.e. cost/MJ presented as US$/MJ. The cost analysis per megajoule adopted similar system boundary as applied in the Life Cycle Assessment (as explicitly described in Chapter 4). It considered the rural and urban context analysis. The rural context included feedstock collection, feedstock processing and use/consumption while the urban context analysis only considered the cost at the use/consumption phase since it was assumed that the upstream costs (such as feedstock collection, processing and transportation) were already included in the purchase price (market price) of the energy carriers.

The cost of energy per megajoule applied an equivalent functional unit of 1 megajoule of heat delivered to pot; similar to that used in the LCA. The Life Cycle Inventory (LCI) of the LCA gave the amounts of flows for each of the selected value chains. The respective costs were multiplied with the flows i.e. LCI based LCC methodology. The cost of labour in the agricultural sector (unskilled labour) in Kenya and Tanzania was applied when calculating the cost of labour; 29.97 Ksh/hr and 228.30 Ksh/day (GoK, 2015) and 3,846.50 Tsh/day and 512.85 Tsh/hour (United Republic of Tanzania, 2013).

6. 2 Biomass Energy Costs in the Rural Context

6.2.1 Feedstock Collection

Generally, firewood collection largely contributes to the overall life cycle costs per megajoule ranging from 87% to 100% in Kitui along the different value chains. In Moshi, these costs range from 66% to 100%. The use of improved technologies and the corresponding decrease in fuel input can help to reduce the cost per megajoule substantially (Figure 6.1).

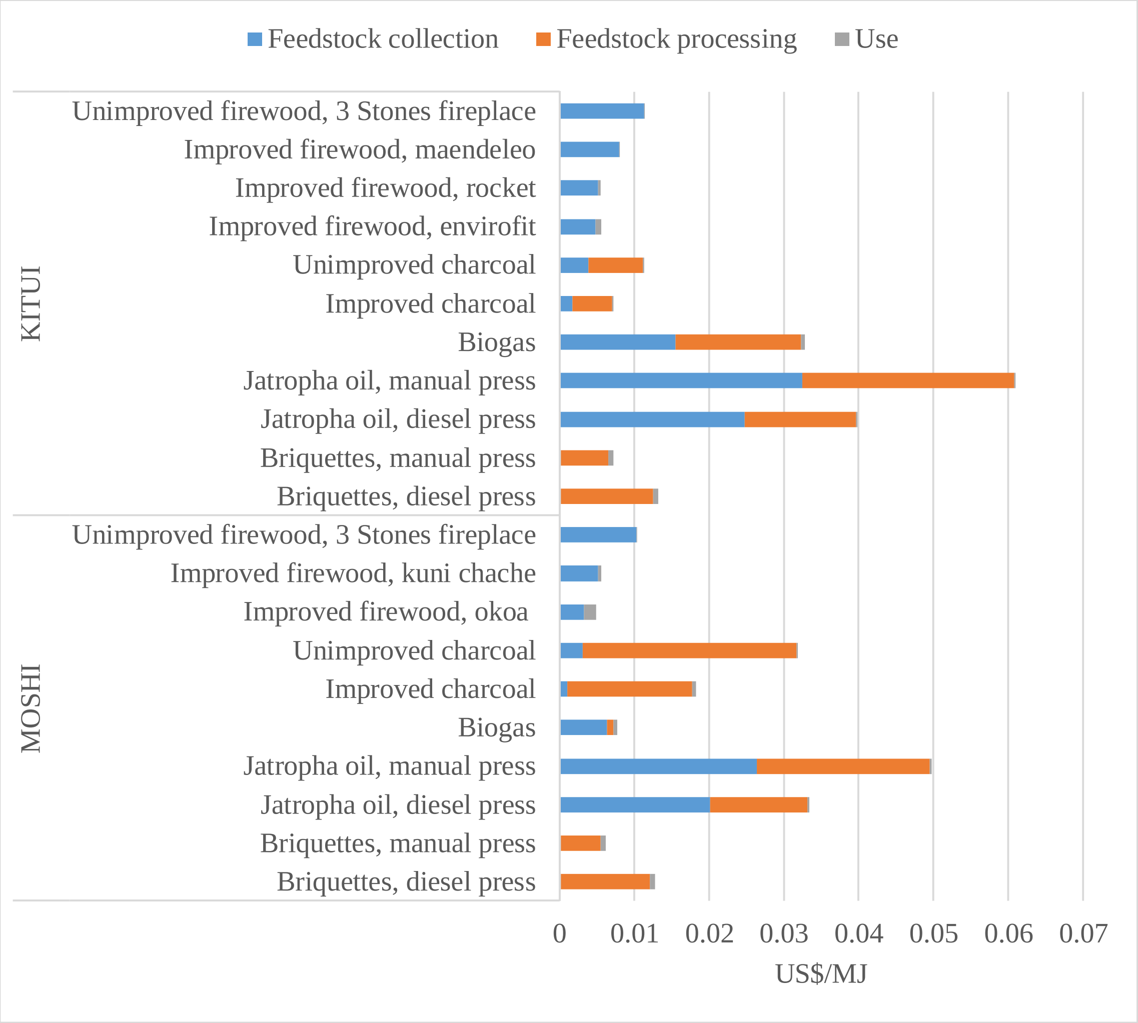

Figure 6.1: Life cycle costs per megajoule (US$/MJ) in the rural context

For instance, in Kitui there is a 30%, 55% and 57% reduction in the life cycle cost per megajoule when using the improved *maendeleo* stove and *rocket* stove and *envirofit* stove, respectively, compared to that of the life cycle costs of the unimproved firewood value chain. Similarly, in Moshi, the life cycle cost per megajoule of feedstock collection declines from 0.01 US$/MJ to 0.005 US$/MJ (*kuni-chache* stove) and 0.003 US$/MJ (*okoa* stove) in the rural context representing 50% and 69% reduction in the cost of firewood collection when compared with the unimproved firewood value chain, respectively.

The analysis applies an average of one and a half hours ($1^1/_2$ hours) to collect one headload of firewood estimated at 17kg. Since firewood collection is characterised mainly by the labour hours spent, use of improved firewood cook stoves leads to a reduction in firewood consumption for every megajoule of heat delivered to pot, therefore, directly reduces the costs. Monetization of labour hours used for firewood collection, which is often considered free, plays a key function in influencing the cost variation of firewood value chain. Unimproved firewood value chain is commonly perceived as the cheapest especially in the rural areas since the materials for building the stove, are in many cases, locally available. However, these results provide a contrary picture indicating that the improved firewood value chains, despite the stoves having high initial purchasing price, provide improved economic impacts as considerably less wood is used to produce the same amount of energy for cooking. In addition to monetization of labour for firewood collection, the cost analysis in Moshi includes government royalty fees. In Kilimanjaro region where Moshi lies, a government royalty fee of 6,500Tsh (2.99US$), is payable for $1m^3$ of firewood harvested. However, the analysis shows that this fee only contributes 10% of the cost per megajoule of firewood collection, which consequently implies that the labour cost remains the most important cost factor of the feedstock collection phase.

Similarly, as in firewood collection, harvesting of wood for charcoal making is often done by household members. This labour is always considered free since it is not directly paid. The improved charcoal value chain due to combined improved efficiency of the kiln and the cook stove reduces the amount of wood required to deliver one megajoule of heat to pot. Consequently, the cost of labour reduces by 55% and 67% in Kitui and Moshi, respectively. The cost per megajoule is consistent with the reported reduction in the wood demand in Kitui and Moshi, respectively.

For biogas, the collection costs in Kitui are more than twice as high as in Moshi. This is due to the different grazing systems prevailing in these areas. In Kitui, the study considered the collection costs for a free-range system of cattle rearing while in Moshi rural the study adopted zero grazing of cattle. With an average of three cows per household, the study estimated that one needs approximately 30 minutes ($^1/_2$ an hour) to wash out the cow dung in a zero-grazing system into the biogas digester. On the other hand, the study estimated that in Kitui, an equal amount of dung is collected in 1 hour since it is scattered and has to be manually transferred to the preparation site. In the rural context of Kitui, the results show that collection of cow dung for biogas production contributes 47% to the overall cost of the biogas value chain.

In general, collection of the feedstock in the jatropha oil manual pathway chain is 24% higher than the cost per megajoule in the jatropha oil diesel value chain. The collection of jatropha seeds is labour intensive contributing up to 53% of the overall cost of jatropha oil manual value chain in Kitui and Moshi. Therefore, application of the diesel oil press due to its better oil production efficiency (80%) reduces the labour input needed for an equivalent amount of jatropha oil. The manual press with a production efficiency of 60% requires an average of 5.25 kilograms while the diesel press with an efficiency of 80% requires 4 kilograms of seeds to produce one litre of jatropha oil (FACT Foundation, 2010). In general, jatropha oil manual value chain has the highest cost per megajoule for feedstock collection stage among the selected biomass energy value chains in Kitui and Moshi while that of the improved charcoal value chain being the least.

Collection of biomass fuel to provide the much needed energy for cooking for the households in rural areas is never paid for (Ingmar & Kees, 2011) despite the fact that women in the rural areas of developing countries devote valuable time and effort at the expense of education and income generation to this work (World Energy Outlook, 2006; Africa Renewable Energy Access Program, 2011). This study, however, indicates that when this labour is quantified and monetarised, the positive impact of utilising improved cook stoves on feedstock collection is evident in economic terms in addition to their role in carbon footprint reduction (Okoko et al., 2017) and health impact.

6.2.2 Feedstock Processing

In both study sites feedstock processing costs vary substantially. For instance, since firewood is used as it is without any further conversion, therefore, it has no cost per megajoule for this stage while jatropha manual press and the unimproved charcoal value chains have the largest feedstock processing costs per megajoule in Kitui and Moshi respectively.

In Kitui, feedstock processing contributes 70% to the overall cost per megajoule in the unimproved charcoal value chain. Labour cost has a large share of contribution in both charcoal energy pathways. In the traditional charcoal pathway in Kitui, a sole contributor to the cost per megajoule of feedstock production is that of labour. In addition to the wood, leaves, twigs and soil for kiln construction which are often obtained free of charge from the surrounding area, the improved basic earth kiln has a metal chimney. The cost of labour in the unimproved value chain exceeds that of the improved value chain by up to 33%. In addition to direct labour costs, charcoal production in Tanzania attracts government royalty fees. The inclusion of the royalty fees in Moshi has a significant influence on the cost of feedstock production with the unimproved charcoal having a cost of 0.03US$/MJ while that of the improved charcoal value chain is to 0.02US$/MJ. Of these costs, the royalty fees has the largest share making up to 86% and 74% of the total cost of feedstock production (charcoal production) for the unimproved and improved charcoal value chains, respectively. 95% of the royalty fees (5.77US$/50 kg bag of charcoal or 12,500Tsh/50 kg bag of charcoal) goes to the central government, while 5% of these fees goes to the local government. In the rural context of Kitui, feedstock production stage of the unimproved charcoal value chain has a life cycle cost of 0.01US$/MJ, while that of the improved charcoal value chain is 0.005US$/MJ. To conclude, the life cycle cost of charcoal production in Moshi exceeds that of Kitui by up to 80%.

In the rural context of Kitui, feedstock processing for biogas production contributes 51% to the overall cost/MJ of the biogas value chain. In the context of free range cattle keeping system as considered for Kitui, it takes a person an average of one hour to prepare the feedstock and feed it into the digester. Of the overall cost/MJ, the largest cost is allocated to labour; 92% while only 8% is allocated to the cost of the plastic biogas digester. The biogas value chain is characterised by large investment cost of the biogas digesters which many a times is out of the reach for many households. Biogas systems are often installed at the household level and, therefore, all the financial burdens are borne by the household. Therefore, installation of biogas system is often limited to those who can afford other sources of modern energy such as LPG (ETC Group, 2007). Despite the high initial purchase and installation cost of the digester, per megajoule calculation of the digester based on its 5 year lifespan significantly reduces the portion of the digester allocated to deliver 1 megajoule of heat to pot thus its lower contribution to the total cost per megajoule.

In the rural context of Moshi, feedstock processing for biogas production contributes 8% of the total life cycle costs along this value chain which is wholly allocated to cost of VACVINA digester. This is because in a zero grazing system, it is possible that the cattle shed is directly connected to the VACVINA bio-digester and, therefore, during cleaning, the feedstock is already channelled into the bio-digester thus allocating all the labour to the feedstock collection phase. Although the cost of installing a single biogas digester is high posing a major challenge to adoption of biogas technology (Muvhiiwa et al., 2017), the unit of digester per megajoule reduces, when its lifespan estimated at 15 years for the VACVINA bio-digester is considered.

In the rural context of Kitui and Moshi, feedstock processing in the jatropha oil manual value chain is 47% and 44% higher than that of the jatropha oil diesel press value chain in Kitui and Moshi, respectively. In both cases, labour cost plays a significant role. Similarly, the allocation of labour in the crop residue briquette manual value chain is quite significant: 72% and 67% in Kitui and Moshi, respectively. However, in the diesel value chain, the contribution of labour is considerably low compared to the manual value chain. It contributes only 4% to the overall life cycle cost of briquette processing while that of the press is considerably high: contributing 72% and 73% in Kitui and Moshi, respectively. The manual briquette presses are easy to use requiring low levels of skills. In addition, they do not require huge initial cost and are cheap to operate. However, they require higher labour input compared to the diesel powered press machines to produce an equivalent amount of crop residue briquettes. In general, feedstock processing stage in the diesel press value chain is larger than that of the manual press value chain by 49% and 56% in Kitui and Moshi, respectively. Ngusale et al. (2014), estimates that the manual briquette press produces briquettes at the rate of 12kg/hour compared to

100kg/hour by the diesel powered briquette press. As such, the diesel briquette press significantly reduces the labour cost per megajoule. However, this high labour cost of the manual briquette press is offset by the higher cost of the diesel press machine; 294 US$ and 1,469US$, respectively, in addition to the fuel cost, which contribute 23% of the feedstock processing stage. The net effect is a higher cost of feedstock processing by the crop residue diesel press value chain as compared to the manual press value chain.

6.2.3 Use/Consumption

As generally observed, the use stage in the biomass energy value chains studied in the rural context has the least contribution to the cost per megajoule. This contribution, however, may vary among different value chains. In this stage, the cost per megajoule of the selected value chains includes the cost of the stove but excludes that of fuel. Inclusion of the cost of fuel would amount to double counting of upstream costs (i.e. cost of feedstock collection, feedstock processing and transport of the biomass energy).

In the rural context of both study sites, use of the three stones fireplace presents the lowest cost per megajoule contributing <1% to the overall cost per megajoule of the unimproved firewood value chain. This is also confirmed by Afrane & Ntiamoah (2012). In some instances, households use clay bricks since natural stones are not available. This study indicates that even when the clay bricks are used, the cost per megajoule remains quite insignificant. By contrast, the cost per megajoule of the improved firewood value chains is larger by 83% (*maendeleo* stove), 90% (*kuni- chache* stove), 95% (rocket stove) and 97% (*envirofit* stove and *okoa* stove) largely attributed to the higher purchasing price of the improved stoves. Comparatively, the *envirofit* and the *okoa* stoves have higher purchasing/installation costs than the rest of the firewood stoves studied. For instance, at the time of study, the average price of the *envirofit* was 39US$ while the installation of the *okoa* stove in Moshi required up to 138US$. In general, the improved firewood cook stoves provide an economic advantage to households since they substantially reduce household expenditure on firewood when compared to the 3 stones fireplace due to reduced firewood consumption as also expressed by Ochieng et al. (2013) in their study in Western Kenya. Reduced firewood consumption offer vital implications for strategies aimed at reducing the burden of collecting firewood by households in the rural areas and the related opportunity cost; together with those targeting impacts of firewood collection on the surrounding environment.

According to Ochieng et al. (2013), firewood stoves with better efficiencies have the potential of offering short-term remedies even as long lasting answers are pursed since the supply of firewood often does not meet the high demand for firewood. Even as households in the rural areas continue to live with inadequate supply of energy, one of the key challenges remains the continued reliance by households on solid biomass fuels. The use of energy conserving and wood saving technologies would thus help bridge the gap of supply-demand deficit for firewood. Heavy dependence on biomass means that considerable amount of time is allocated to its collection or substantial expenditure if bought. Therefore, properly designed programs of improved cook stoves can offer numerous advantages for households (Bailis et al., 2007). However, households often do not have sufficient cash available for investment costs of an improved cook stove. Thus saving and credit facilities for energy related investment could help overcome this hurdle.

6.3 Energy Costs in the Urban Context

In the urban context, the cost of the studied biomass fuels and the costs of the selected stoves are calculated per megajoule. The fuel cost adapts the market price of the fuel since biomass fuels in the urban context are bought from the local markets. This cost of the fuels assumes that the upstream costs (feedstock collection, processing and transportation) are already included in their market price and, therefore, the need to avoid double counting of costs. Therefore, the urban context analysis is based on the type of fuel and stove without distinguishing the different stages of biomass energy. For instance, the market price of jatropha oil and briquettes is used not considering the production technology. Generally, the use cost per megajoule of heat delivered to pot in Kitui and Moshi is considerably lower compared to that of the biomass fuels. In the urban context of Kitui and Moshi, cooking with the three stones fire place is the most expensive among the firewood value chains (Figure 6.2).

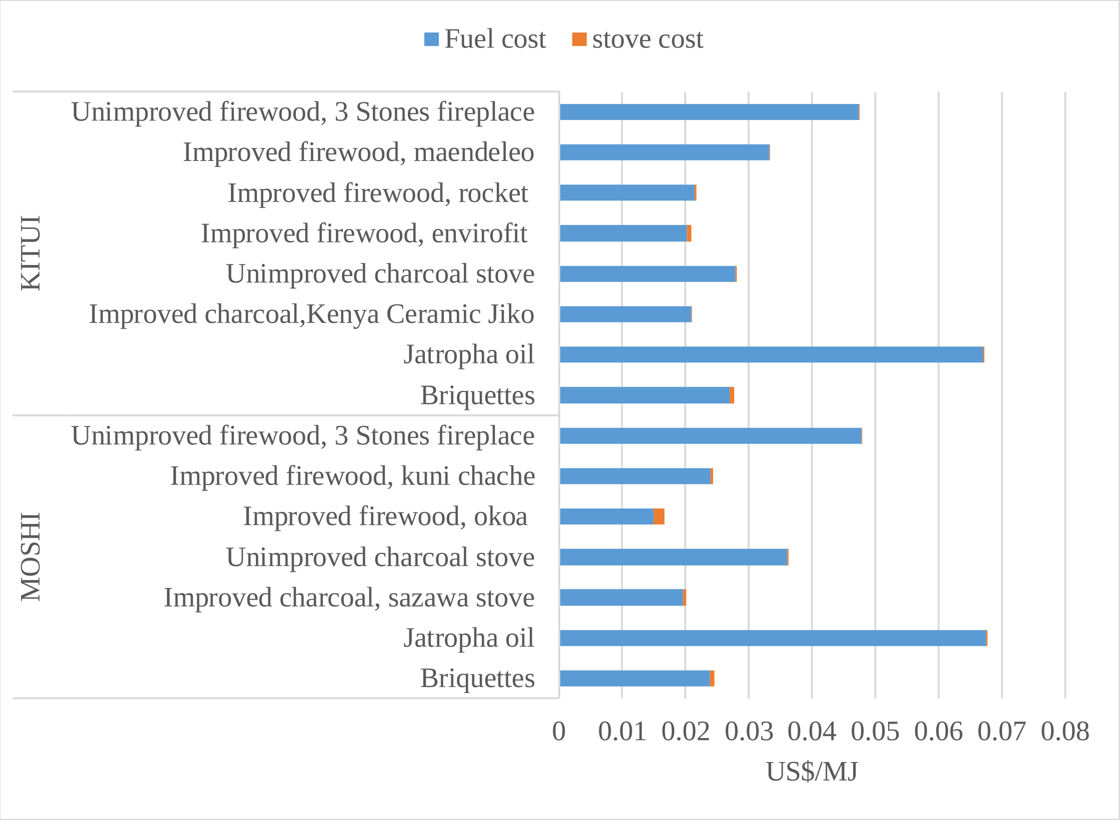

Figure 6.2: Life cycle costs per megajoule (US$/MJ) in the urban context

Although firewood is generally considered as the cheapest cooking fuel (Afrane & Ntiamoah, 2012), this study indicates that the cost per megajoule reduces with improvement in thermal efficiency of the firewood cook stove. In Moshi market, 1kg of charcoal retails at 500Tsh (0.23US$) while a bundle of firewood which weighs 17kg is sold at 4000Tsh (1.85US$). The fuel required to deliver the heat to the cooking pot; determined by the stove efficiency and fuel energy content; is however higher for unimproved firewood i.e. 0.44kg wood per megajoule of heat delivered to pot while that of unimproved charcoal is 0.16 kg per megajoule of heat delivered to pot. This, therefore, results in a higher cost per megajoule when the unimproved firewood stove is used (Figure 6.2), a scenario which changes with use of the improved firewood stoves efficiency as is with the *okoa* stove.

Of great interest is the gradual decline of the cost per megajoule of the improved stoves (firewood and charcoal) when spread across the lifespan compared to the cost of fuel (Figure 6.2) as opposed to their lump sum initial purchasing price. This is an indicator that adequate cost mechanisms or incentives have the opportunity to influence adoption of improved biomass energy technologies that are otherwise expensive, making them inaccessible (World Energy Outlook, 2006; Africa Renewable Energy Access Program, 2011). Important to note, heavy dependence on biomass energy for cooking is associated with huge financial burdens (Lambe et al., 2015). Additionally, continued reliance on unimproved stoves by the rural and urban poor households will lead to over consumption of biomass and consequently increased forest degradation (Chagunda et al., 2017). Furthermore, use of traditional biomass energy has undesirable effects on health with approximately 600,000 deaths occurring annually in Sub-Saharan Africa as a results of exposure to biomass smoke (Lambe et al., 2015).

6.4 Overall Comparison of Biomass Energy Pathways

6.4.1 Life Cycle Stages

The costs of using is minimal (cost of stoves) compared to the fuel costs (collection, processing or fuel costs in urban areas) in all sites and contexts. But the efficiency have a substantial impact on the fuel costs. Labour investments play a crucial role in cooking energy.

6.4.2 Comparison of Fuels

Most cost efficient is firewood if used with improved cook stoves with higher stove efficiencies. In addition, use of improved stoves leads to a reduction in the carbon footprints and indoor air pollutants thus providing an environmental and health benefit. Charcoal shows a very mixed picture. The context specific differences are crucial. The results indicate that the royalty fee in Moshi is not visible in the market price. This can be due to the fact that the charcoal available in the market in Moshi is not produced locally due the law prohibiting charcoal production within Kilimanjaro region since 2012. Charcoal available in markets in Moshi is often transported from other regions such as

Tanga (Oral communication from the Kilimanjaro Regional Natural Resources Office and Tanzania Forest Service). Briquettes, it seems from an economic point of view, are in a price range making them competitive with charcoal. The cost of biogas is, however, dependent on the technology and the type of livestock herding. Among the alternative biomass fuels, biogas is not as competitive as briquettes in Kitui's rural context due to the constraints of dung collection which in the long run is not feasible in addition to other factors. As reported by Lwiza et al. (2017), the labour that sustains the adoption of biogas is often dependent on family members, more so children. Absence of this labour makes its adoption difficult. However, in Moshi's rural context, adoption of the zero grazing system of cattle rearing could provide a desirable source of fuel adding to the lists of biomass fuel options for the population.

Despite the potential by briquettes to provide an economically viable alternative biomass fuel in both study sites and contexts, a report on the Kenya Briquette Industry by GVEP International (2010) observes that the penetration of briquettes remains low in the rural set-ups simply because firewood is collected from the surrounding areas at no cost, making it difficult to substitute firewood with briquettes despite its promotion in Kenya, Tanzania and Uganda. However, the GVEP International (2010) report states that in situations where firewood is not available and charcoal has to be bought, then briquettes would become a substitute in the rural areas. However the monetization of labour hours used to collect firewood, gives a contrary outlook whereby the household energy cost of briquette value chain is 41% lower than that of the unimproved firewood value chain in Kitui's rural context. In addition, the analysis of the urban context of household energy indicates that the annual household energy cost of briquette use is almost similar to that of improved firewood where rocket, *envirofit* and *okoa* stoves are used.

Clough (2012), states that the substitution of traditional sources of fuels with briquettes is faced by challenges such as perceptions of the users, costing, and accessibility of briquettes. In a more optimistic scenario it is projected that some consumers would switch to briquettes due to their convenience compared to collection and keeping of firewood and the longer burning period, however, this will be based on its attractive pricing (International Energy Agency, 2014). In addition, drivers to serious campaign for adoption of alternative sources of fuel include forest degradation and regulation by government bodies. International Energy Agency (2014) reiterates that if the solid biomass remains cheap or free relative to the alternatives, then even an increase in incomes may not be a critical trigger for households to switch to modern fuels. Stimulating the briquette markets is, therefore, one intervention necessary in efforts aimed at supporting efficient biomass energy usage (Energy and Environment Partnership, 2013). Jatropha has the highest costs in both sites and context, even if it is processed more efficiently using a diesel press.

6.4.3 Comparison between Sites and Contexts

Generally, a similar pattern is seen between Kitui and Moshi. However, the cost of charcoal in Moshi is complicated by the inclusion of royalty fees making the cost of charcoal higher than in Kitui. Biogas in Kitui is not attractive due to the cattle herding system, which requires a lot of labour. The cost of the biogas technology also plays a role in influencing the total cost of the biogas value chain in the rural context of both study sites. For instance, the high unit cost of the VACVINA biogas digester significantly contributes to the feedstock processing in Moshi while that of the plastic biogas digester is insignificant. The market prices in the urban areas do not reflect the picture of the rural area, i.e. rural costs plus transportation cost. The explanation is more complex as market mechanisms play a role; scarcity of supply, origin of charcoal (in Moshi charcoal is from outside the region), taxes, (both legal and illegal), which are passed on to the consumer.

6.5 Summary

The study shows that the cost contribution of improved stoves to the total costs per megajoule are not important, since they seldom exceed 5%. This indicates that with appropriate payment schemes, the higher costs of improved stoves will not be a limiting factor when it comes to their adoption. The costs per megajoule delivered to pot are dominated by the fuel provision (feedstock collection and processing). Bearing this in mind, any increase in stove efficiency will have a large effect on fuel costs and, therefore, reduce costs per megajoule (and also environmental impact) significantly. It is, therefore, necessary that relevant payment schemes to support the adoption of improved stoves are introduced or enhanced; for instance introduction of a “flat rate”, where poor households receive a modern stove (free of charge) and only have to pay a monthly allowance for the required fuel input (which is far less than the fuel costs associated with a low-efficiency stove).

CHAPTER SEVEN

ECO-EFFICIENCY OF ALTERNATIVE VALUE CHAINS FOR BIOMASS ENERGY FOR COOKING

7.1 Introduction

This section presents the integrated results of the life cycle assessment and life cycle costing of the selected biomass energy value chains; carbon footprints and the cost per megajoule; to give the eco-efficiency of the selected biomass energy value chains.

7.2 Eco-efficiency analysis

Eco-efficiency in this study is a concept that brings together the two dimensions of biomass energy: ecology and economy. It measures the environmental performance of a product with considerations to its financial performance. Increasing the eco-efficiency of biomass energy can be accomplished by increasing the value of biomass energy. This can be achieved by ensuring a decrease in the environmental impact or resource consumed for the evaluated product (Lyrstedt, 2005). The eco-efficiency assessment is a useful tool that can be used by various stakeholders in the biomass energy sector to track improvement of various products and or processes. In addition, it allows the stakeholders to set goals for improvement of these products, services and processes and finally promotes the efficient inputs and outputs (Nakaniwa, n.d.). In this study, the environmental performance is measured using its carbon foot prints (kgCO_2eq/MJ) while the economic viability is assessed by its cost per unit (US$/MJ) of the biomass energy value chains.

The eco-efficiency analysis is done by plotting both the carbon footprints and the cost per MJ on an XY scatter plot chart in Exce. The eco-efficiency charts gives an indication of the most and least eco-efficient biomass energy value chains based on their carbon footprints and cost per megajoule. In both study sites (Figure 7.1 and 7.2), the unimproved charcoal and jatropha oil manual press value chain appear to be the least eco-efficient. Despite jatropha oil manual press value chain having very low carbon footprint, on the contrast, its cost per MJ is the highest among the selected value chains. Similarly, the unimproved charcoal value chain has very high carbon footprints thus reducing its eco-efficiency rating.

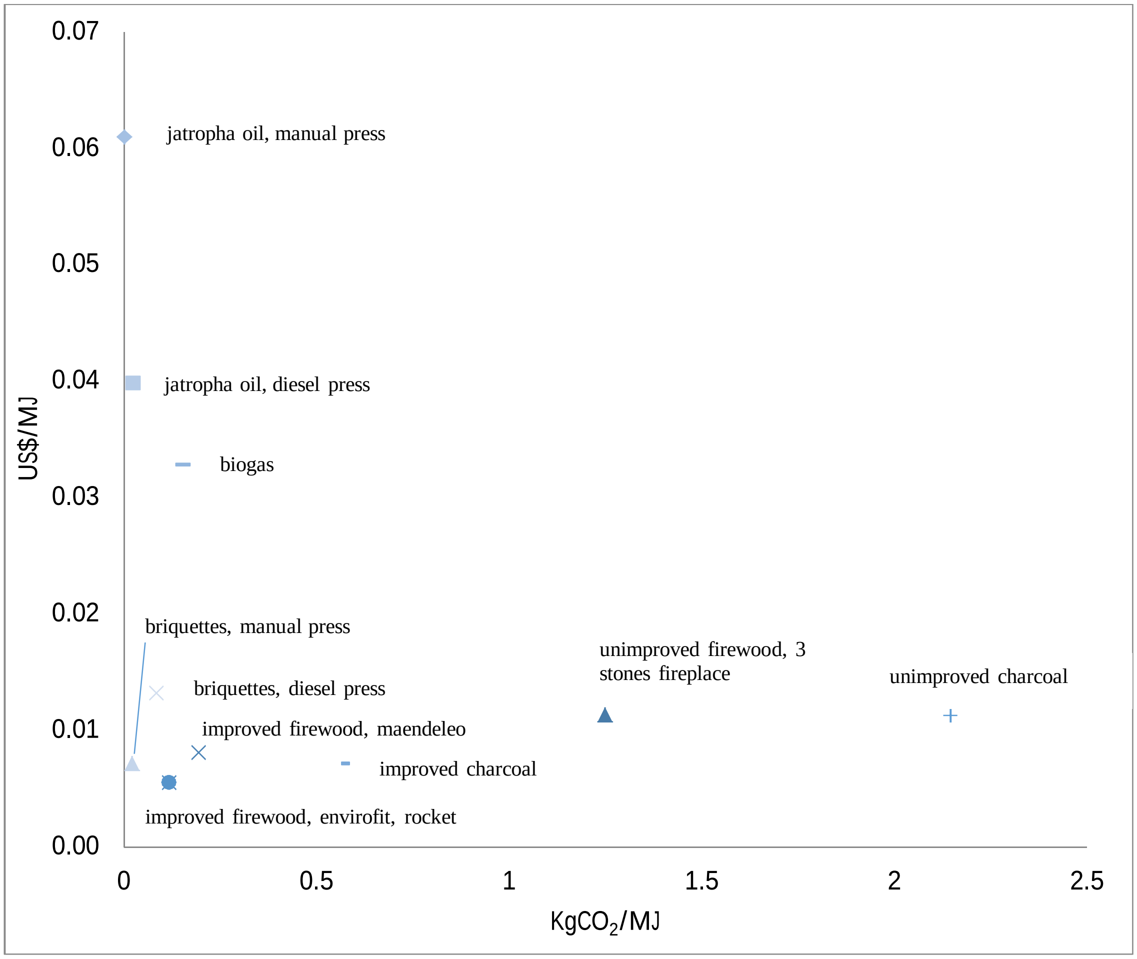

Figure 7.1: Eco-efficiency of biomass energy value chain in Kitui rural

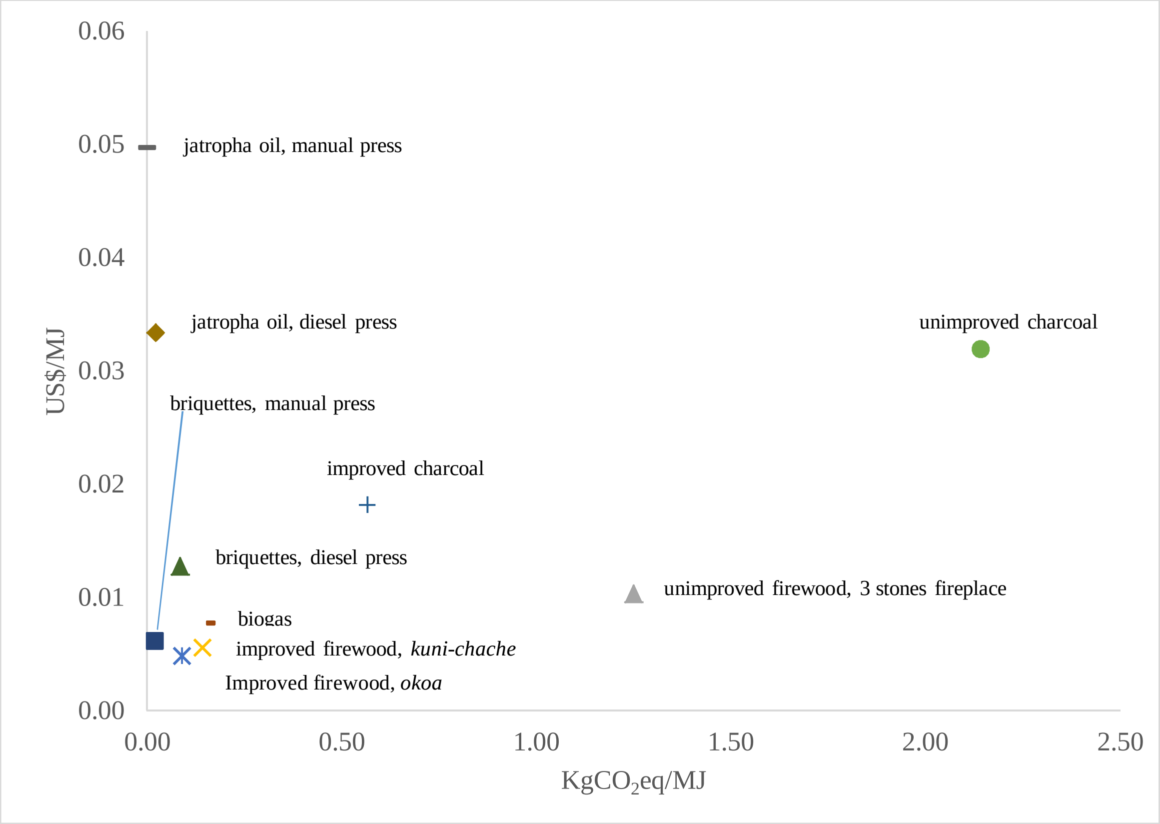

Figure 7.2: Eco-efficiency of biomass energy value chains in Moshi rural

The results presented indicate that use of firewood in improved cook stoves (*envirofit*, rocket and *maendeleo* in Kitui and *okoa* and *kuni-chache* in Moshi), offer better alternatives to charcoal considering their carbon footprints and economic viability. The charcoal value chain is associated with environmental degradation as a result of trying to satisfy the increasing demand of charcoal especially by the urban dwellers. The destructive nature of the charcoal value chain is premised on the fact that charcoal is carbon intensive and uses high amounts of biomass for energy delivered to pot due to massive losses during pyrolysis (Ehrensperger et al., 2017). However, emphasis on use of firewood with improved stoves and well ventilated kitchens is necessary to reduce the negative health impacts due to indoor air pollution, majorly particulate matter. Interesting to note is that the high cost firewood stoves such as the *envirofit* and the *okoa* firewood have better eco-efficiencies than the three stones fireplace, which is considered the cheapest. The high lump sum initial purchasing price of the improved stoves is reduced when the cost is spread across their lifespan. In addition, they have the potential to reduce firewood consumption as is supported by Hafner et al. (2018), therefore, reducing substantially expenditure on firewood; in terms of cash spent while purchasing firewood or labour hours spent on collection. From these results, it is thus important that appropriate payment schemes are adopted to support the adoption of the improved stoves due to their multiple benefits of reduced carbon footprints, costs and negative health impacts.

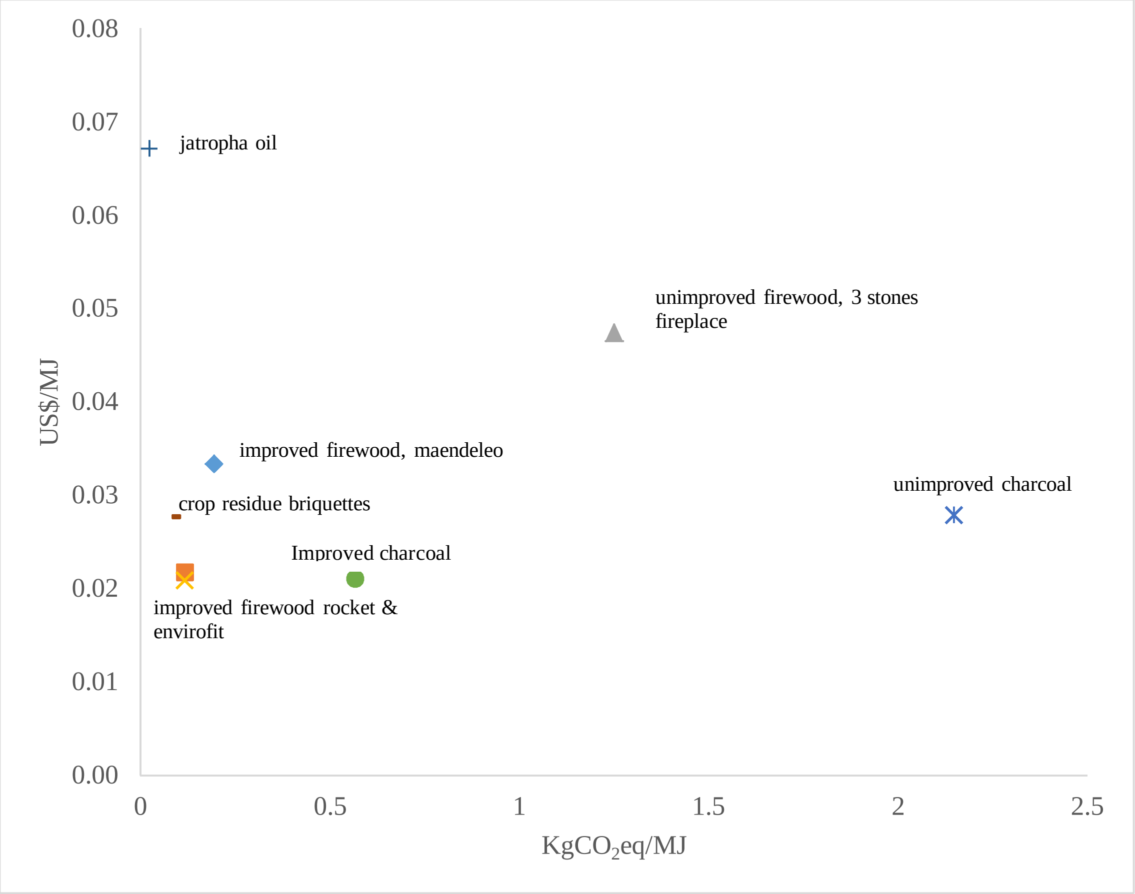

Figure 7.3: Eco-efficiency of biomass energy value chains in Kitui urban

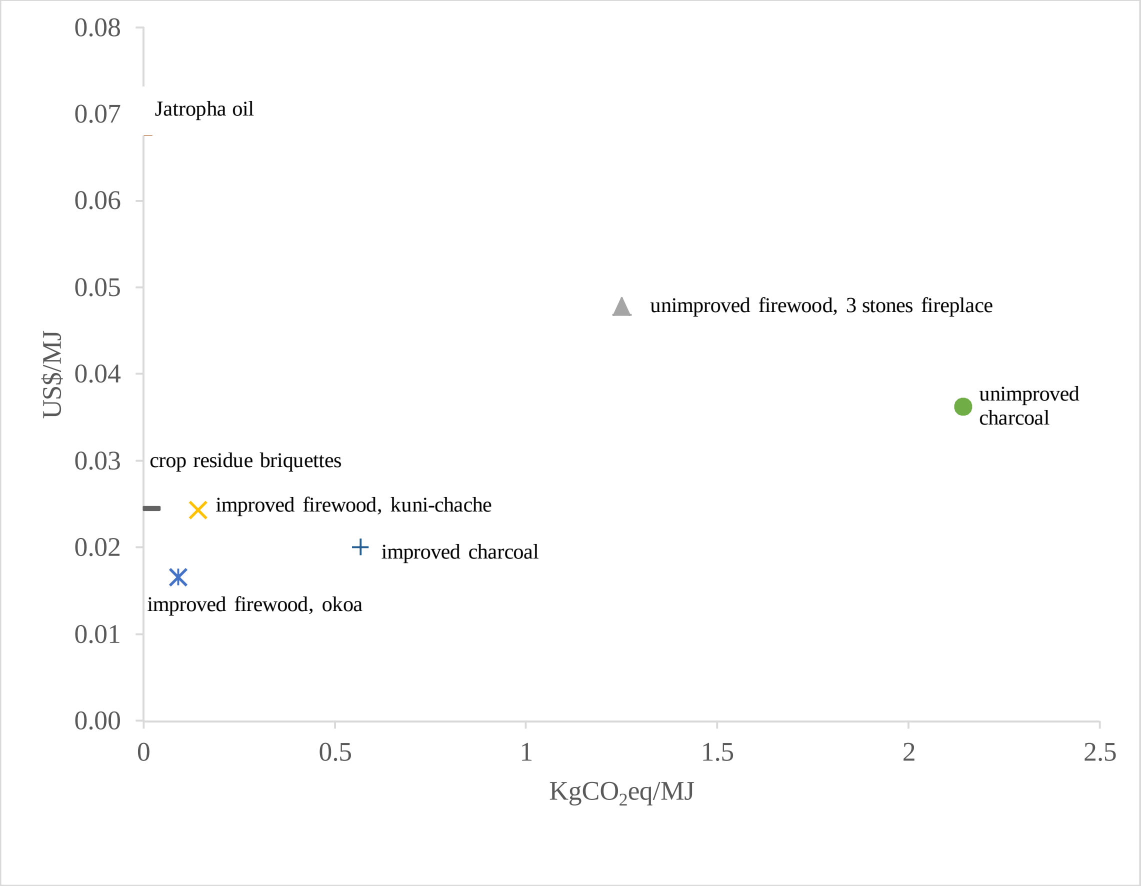

Figure 7.4: Eco-efficiency of biomass energy value chains in Moshi urban

According to Santoyo-Castelazo & Azapergic (2014), there is no overall best scenario, as each option studied is better for some sustainability criteria but worse for others. The eco-efficiency framework applied in this study, therefore, indicates the potential for diversification of biomass energy fuels. In the rural contexts of Moshi, biogas and crop residue briquettes offer eco-efficient alternative fuels to wood-based biomass energy solutions. In addition to reduced carbon footprint and costs per megajoule delivered to pot, biogas digesters provide a cleaner cooking fuel which is more flexible and of higher quality than charcoal and firewood (Garfi et al., 2012; Tigabu et al., 2015b). This consequently helps in reducing indoor air pollution and incidences of respiratory diseases. Combustion of biogas does not produce particulate matter emissions though the hydrogen sulfide (H_2S) content is a major concern (Garfi et al., 2012), and, therefore, improving household health conditions/status. However, biogas in Kitui may not be eco-efficient. This is attributed to the high cost associated with the labour used for the collection and preparation of feedstock in a set-up where free range cattle raring system is adopted.

Crop residue briquettes due to their eco-efficiencies are best placed to provide alternative biomass energy to firewood and charcoal (GVEP International, 2010) in Kitui and Moshi. The suitability of crop residue briquettes as alternative sources of biomass energy cut across the urban (Figure 7.3 and 7.4) and the rural context. As such, biomass energy strategies should pay special attention to high-quality non-carbonized briquettes made from farm residues, woodchips, sawdust, or woody biomass residues (Ehrensperger et al., 2017).

7.3 Summary

The eco-efficiency results indicate that biomass energy strategies need to shift their focus to alternative sources of biomass energy such as briquettes from crop residues. These alternatives are eco-efficient since they have a low carbon footprint and low cost per megajoule compared to charcoal which is carbon and resource intensive. Jatropha oil, despite having the lowest carbon footprint is, however, not cost efficient, therefore, falling below the bar of eco-efficient biomass energy fuels studied. Additionally, the study indicates that the biomass energy strategies need to diversify the energy solutions that fit different consumers' needs since there is no-one-fits-all solution for cooking energy.

CHAPTER EIGHT

SUMMARY OF RESEARCH FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

8. 1 Introduction

This chapter presents a summary of the research findings as guided by the specific objectives of the study. It also presents the conclusions of the study and goes ahead to give recommendations which can help improve the biomass energy value chain in Kitui, Kenya and Moshi, Tanzania. The recommendations are divided into two parts; policy recommendations and recommendations for future research.

8.2 Summary of Research Findings

8.2.1 Carbon footprints of Biomass Energy

Generally, the feedstock collection phase of the firewood and the traditional charcoal pathway considerably contributes to greenhouse gas emissions. The analysis discloses that a shift from firewood to charcoal will aggravate the already degraded environment, since its greenhouse gas emission is higher than that of firewood. Methane emission during biogas use essentially influences its carbon footprint. In general, the jatropha oil value chain featuring use of a manual oil press seems to offer the highest potential for decreasing carbon footprints in both contexts and study sites. Nevertheless, its potential might be constrained due to the inadequate quantity of jatropha seeds that can be cultivated in along the hedges on individual farms.

8.2.1 Life Cycle Costs of Biomass Energy

The results presented show that across all the selected biomass energy value chains, the cost of labour at the feedstock collection and the feedstock processing stages are large. In developing countries, collection of firewood and production of charcoal are often considered free since these activities often involve household labour. However, monetization of the labour indicates that a substantial amount of cost is involved across the value chain. Improvement of kiln and stove efficiency have a direct impact on the amount of resources required by the upstream process; i.e. feedstock collection. Since the main cost associated with charcoal making using the selected technologies is that of labour, reduction in feedstock amount to be collected, therefore, directly impacts on the cost. Firewood and charcoal are also always considered cheap since many charges imposed are often not documented or official. However, the inclusion of royalty fees as seen in Moshi changes this scenario. Though the jatropha oil value chain has low carbon footprints prior familiarity with jatropha in East Africa indicates limitation in its economic feasibility. From this study, it is clear that the economic sustainability of the jatropha oil value chain even from a life cycle perspective is limited.

8.3.1 Eco-efficiency of Biomass Energy

The results indicate that in the rural and urban contexts, improvement in the efficiency of wood-based value chains reduces their carbon footprints and cost per megajoule. This, therefore, makes them of better eco-efficiency than the charcoal value chains. Replacing firewood with charcoal will be detrimental. The results also indicate that biomass energy value chains such as biogas and briquettes offer viable alternative to the wood-based fuels from an eco-efficiency perspective.

8.3 Conclusion

Evaluation of the carbon footprints of biomass energy pathways offers support for the development of relevant policies and strategies of producing and utilising biomass energy. The results can help decision-makers appreciate the causes and extent of certain impacts of biomass energy, enabling them to pay special attention to points along the pathway that require improvement as a way of achieving development on the path towards achieving socially acceptable development. The study results provide pertinent information on ecological performance, cost viability and eco-efficiency of biomass energy value chains. The information is useful for creating awareness and informing stakeholders and decision makers on the suitability of biomass energy solutions based on different parameters. This creates opportunities for development of other biomass energy options. Generally, the study results show the potential for diversification of energy pathways based on their eco-efficiency performance. However, there is no overall best scenario, as each option studied is better for some sustainability criteria but worse for others. Nevertheless, the answers depend upon the improvement of biomass sources for energy production by encouraging forest cultivation, designing better stoves, constructing better kilns and stoves and lastly encouraging adoption of alternative fuels such as biogas and briquettes.

8.4 Recommendations

The results presented in this research give information on carbon footprints, the life cycle costs of selected biomass energy value chains and finally their eco-efficiency. This information is aimed at contributing to the policy decision process within the energy sector in both study sites. As such, the study provides policy recommendations, as well as recommendations for future research.

8.4.1 Policy Recommendations

Government and Development Agencies

1. *Use of LCA and LCC as tools for evaluation*

Adoption of LCA and LCC as innovative evaluation tools for technologies meant for development interventions in developing countries can be encouraged in all aspects of development initiatives in order to realise positive development impact not only locally but also globally. The aim of advocating for their introduction and adoption is to ensure that the development interventions in all the fields; biomass energy included; generate positive impacts. This is expected to have a trickle-down effect on human: health, the ecosystem and natural resources through emission reduction, reduction in natural resource consumption, reduced land, forest and water degradation and biodiversity conservation. As evaluation tools, LCA and LCC are applicable in development interventions for sustainable development. They are useful in evaluating technologies right from the initial stages of development through their implementation. These tools, therefore, come in handy especially in developing economies by identifying the areas for improvement along the whole value chain of biomass energy value chains so as to bring positive impact.

2. *Enhanced financial, policy and technical support for biomass energy*

Government, both at the national and regional level, needs to enhance financial, technical and policy support for the improvement of biomass energy value chains such as firewood and charcoal. Financial support is vital for promoting research on biomass energy and in addition, supports extension services geared at promoting sustainable natural resource management. Improving the wood-based biomass energy value chains largely rely on improving general management of existing forests, such as, making sure there exists a replanting approach, without which wood usage is worse than the other options. Efforts should also be made towards encouraging use of dead wood as a source of fuel for cooking due to its reduced emission levels. Improving general management of forests can be done through instituting “friendly” fuel acquisition mechanisms especially for those who live around or near forests. This can be applied as a way encouraging community forest management contrary to the very restrictive measures. Crop residue briquetting should be encouraged and also integrated into the development of biomass energy policies as a viable option with the potential to offer low carbon footprints and low cost per megajoule. There is also need for technical capacity building on briquetting technology to enable the production of quality briquettes, which are able to effectively compete with conventional charcoal.

3. *Identification of market gaps for briquette technologies*

Strategies for scaling up crop residue briquetting should target marketing gaps in the briquetting industry in addition to identifying suitable entry points for the technologies. This is aimed at increasing awareness on briquetting technology and consequently their adoption, a strategy which can help reduce the pressure on wood-based biomass energy sources. Additionally, adequate costing mechanisms are needed for crop residue briquettes to be competitive with charcoal. Proper market structures both for the presses and crop residue briquettes, would ensure that household have a wide range of options in the biomass energy market to choose from.

4. *Improvement of alternative biomass energy pathways*

In order to achieve considerable reduction of methane emission, it is crucial that improvement of the biogas burners and the gas distribution networks is properly done. This is crucial since it aims at reducing significantly methane leakage from the biogas systems. Additionally, the biogas burners need to be made suitable for household cooking needs to enhance adoption of this alternative source of energy. Households need cooking apparatus that have the potential to suit their cooking needs considering pot sizes and staple foods prepared.

Households

1. *Enhanced adoption of improved cook stoves*

Adoption of improved cooking stoves such as Kenya Ceramic Jiko and *sazawa* charcoal, e*nvirofit* and *okoa* wood stoves as alternatives of traditional stoves is necessary. The aim is to achieve a substantial decline in the carbon footprint of wood-based value chains.

2. *Encourage adoption of alternative biomass energy options*

Households should explore and adopt the available options of alternative biomass energy. This can only be achieved by households changing their attitudes and perceptions with regards to certain improved biomass energy technologies and the alternative energy sources.

3. *Encourage communal ownership of advanced technologies*

Crop residue briquetting should be encouraged and also integrated into the development of biomass energy policies as a viable option with the potential to offer low carbon footprints and low cost per megajoule. This, however, can only be achieved if the briquette presses are communally owned, therefore, spreading the economic burden across several households. Households can thus come together for the purposes of initiating joint acquisition of briquette and jatropha oil presses. This is expected to improve households' access to alternative energy and also provide them with a source of income.

8.4.2 Recommendations for Further Research

1. *Improvement of the charcoal value chain*

Significant research efforts should be focused at upgrading of the charcoal value chain. The research should focus on the production phase of the improved charcoal pathway, where emission decrease has continued to be very minimal.

2. *Sustainability of jatropha hedges*

Research is needed on the sustainable supply potential of jatropha hedges since this study only recommends the use of jatropha hedges. These hedges may have a limited capacity for seed supply. Prospective studies need to consider aspects of the biophysical environment, in addition, to the economic and social perspectives of jatropha oil as a means of establishing its sustainability in a broad and conclusive way.

3. *Overall sustainability of biomass fuels*

Decision by household involving changing from one source of energy to another is influenced by several factors, among them being economic, social and technical factors. It is, therefore, important that comprehensive research that integrates all these factors is carried out. The information provided would be useful for creating awareness on the sustainability of different biomass energy options available.

4. *Diversification of fuel used by the jatropha oil and briquette presses*

There is need for further research on the carbon footprint and economic viability of other fuels with the potential to power the press. One such fuel is jatropha oil, as an alternative to diesel, which is appropriate for both rural and urban settings. This is aimed at reducing the reliance on diesel to power the presses and thus potentially increasing the viability of the crop residue briquette and jatropha oil value chains. Use of diesel in the presses used for making briquettes and extracting jatropha oil needs to be critically considered for improvement. Use of a powered system with sustainable (substitute) fuels would possibly lead to a rise in the production efficiency of briquettes, allowing households to expand their sources of income.

5. *Promotion of communal ownership of jatropha oil and briquette presses*

It is also important that further research focusses on the profitability of centralised jatropha oil and briquette production through community groups such as women and youth groups, community based organisations among others as a way of encouraging their adoption, in addition to improving their livelihoods.

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APPENDICES

Appendix 1: Questionnaires

Biogas production Questionnaire number: ____________

Introduction

1. Introduce yourself to the respondents.
2. Tell the respondent where you come from (affiliation) and the purpose of your visit
3. Tell the respondent briefly what the project is about:
4. The study aims to evaluate the environmental impacts and economic viability of different value chains for biomass energy. Results from this study will help in policy and decision making in matters concerning biomass energy.
5. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions.
6. Inform the respondent about the duration of the interview (approx. 45 minutes)
7. Inform the respondent on the confidentiality of the questionnaire.
8. Ask the respondent if he/she has any questions.
9. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS.

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name of biogas producer	
Gender	Male ☐ Female ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:______ Latitude:_____ Altitude:_________

Section B: Digester properties

1. Do you currently produce biogas?

Yes ☐ No ☐

2. When did you start producing biogas? ________ (year)

3. Which technology do you use to produce biogas? ______________________

NB: Take a photo of the bio-digester in use

4. What is the:

Volume of the digester? _______________m3

Length ____________m

Height ____________m

Width ____________m

5. What is the lifespan of the biogas digester (How long can the digester be used before replacing it)? _____________

6. What materials are used to make the biogas digester?

Materials used	Quantity	Unit (kg, m)	Cost/unit Ksh	Total cost Ksh

7. Materials' transportation for digester installation

Materials for digester transported	Sources of material (name place)	Transport distance in km	Transport mode used (road, rail etc)	Type of vehicle used (passenger car, lorry, bicycle etc)	Transport cost Ksh/Tsh

8. What is the labour cost for installing the digester _________________ Ksh/Tsh, if no direct costs are involved how much time did it take to install the digester (hours, days etc) ____

9. How often is the digester repaired in a year? ____

10. How much does the repair cost (spare parts, labour etc?)

Section C: Feedstock collection, preparation and digestion

11. What type of feedstock do you use?

Cow dung ☐

Pig waste ☐

Chicken waste ☐

Mixture ☐

Name the mixture often used: ______________________________

Other (s) ☐

Specify ______________________________________

12. Where do you get your feedstock from?

Keep domestic animals ☐

Collect from neighbours at a cost ☐ Indicate the cost per unit of feedstock collected in Ksh ___________

Collect from neighbours for free ☐

Other sources ☐

Please specify ____________________________

13.If you keep domestic animals, please fill in the table

Animal	Number	Comment(s) if any
Cow (s)		
Pig (s)		
Sheep		
Goat (s)		
Poultry (chicken, turkey, ducks etc)		

14.Is there any form of transportation involved during feedstock collection? Ye☐ No ☐

15.If yes please fill in the table

Feedstock type	Feedstock collection site	Distance from collection site to digester site (km)	Transport mode (earth road, tarmac road, rail etc)	Transport type (passenger car, bicycle, truck etc)	Transport cost

16.How much feedstock do you use per day for biogas production? _____________ (kg)

17.How much do you pay for labour to operate the digester (if farm worker is employed)? ________Ksh per month, Note: If farm worker is not employed indicate time needed to feed the digester (in hours or minutes) __________________________

18. On average how much water do you use to prepare the feedstock for biogas production on a daily basis? _______________ (liters)

19. What is the source of water you use to prepare the feedstock for biogas production?

____

20. How long can you cook with the biogas produced

Meal cooked (name specific food items)	Time needed to cook (include units e.g. minutes, hours)
Breakfast	
Lunch	
Supper/dinner	

21.Do you use the digestate (stuff from the biogas digester) in any way? (If No answer Qn.22, if Yes No go to Qn 23-25)

Yes ☐ No ☐

If No, where do you take it to?

____

____

____________22.If yes, how do you use it?

Fertilizer for garden ☐

Sold ☐ Indicate selling price per unit in Ksh_______

Given away for free ☐

Fish pond ☐

Others ☐

Please specify ____

23. If used as a fertilizer, what method do you use to apply it in the garden?

Manually (e.g. using buckets, hoes, spades etc) ☐

Motorized (use of tractors etc) ☐ Indicate amount of fuel used if this option applies _____ litres/ha and

Name the specific motorized machine/system used (if possible take photo) _______________________________________

24. What benefit has it brought to you when using the digestate as fertilizer?

____

___

25. If No, where do you take it?
26. Briefly describe how the digestate is removed from the digester

27. Do you store the digestate before using it in any of the ways listed in Question 21 above? Yes ☐ No ☐
28. If yes, what type of storage facility do you use?
Open storage facility ☐
Closed storage facility ☐

Additional comments (if any)
29. Are you interested and willing to answer more questions in future?
Yes ☐ No ☐

Any additional comments

30. Who else is producing biogas in this area? (Name, mobile phone and location)

Thank you!!

Charcoal producer Questionnaire number: _________

Introduction

1. Introduce yourself to the respondent.
2. Tell the respondent where you come from (affiliation) and what the purpose of your visit
3. Tell the respondent briefly what the project is about:
4. The study aims to evaluate the environmental impacts and economic viability of different value chains for biomass energy. Results from this study will help in policy and decision making in matters concerning biomass energy.
5. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions. Inform the respondent about the duration of the interview (approx. 45 minutes)
6. Inform the respondent on the confidentiality of the questionnaire.
7. Ask the respondent if he/she has any questions.
8. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS.

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name of charcoal producer	
Gender	Male: ☐ Female: ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:_______ Latitude:__________ Altitude:_______

Section B: Wood Production

1. Do you currently produce charcoal? Yes ☐ No ☐
2. When did you start producing charcoal? ________ (year)
3. Where do you obtain the wood you use for charcoal production?

Collect dead wood ☐
Natural forest ☐
Single trees in between agricultural land ☐
Own plantation ☐
Buy the wood ☐ Price per unit purchased ____ Ksh / ____
Others, please specify ☐
____

4. Are there any reforestation activities for the woodlands and/or forest from which you obtain wood for charcoal?
   Yes ☐ No ☐

5. If yes, who does the reforestation?
   Individuals ☐
   Community members/groups ☐
   NGOs ☐
   Government ☐
   Others, please specify: ____
6. If No, what is the land used for after the trees have been cut for charcoal production?
   Left as waste land
   Growing annual crops
   For settlement (building houses)
   Left for forest to re-grow
   Others
   Please specify ____
7. Do you use any machinery harvesting the wood you use for charcoal? Yes ☐ No ☐
8. If yes, please fill in the table? (Take a photo of the machine if possible)

Machine used for wood harvesting	Amount of fuel used (L/charcoal production cycle)	Cost of buying machine Ksh	Maintenance costs (spare parts, labour for repair etc) Ksh	Where machine was bought

9. If No, how do you harvest the wood? ____

Section C: Kiln properties, charcoal production & packaging

10. Which kiln do you use for producing charcoal? ____________________ *Sketch kiln in the space provided or take a photo*

11. What is the lifespan of the kiln (How long is the kiln used)? ____________________
12. How often is the kiln repaired? ___________________
13. What materials are used to make the kiln you are using?

Materials used	Quantity	Unit (kg,m)	Transport mode (tarmac/ earthen road, rail etc)	Distance (km)	Type of transport (truck, passenger car, bicycle etc)	Transport cost Ksh	Other cots
							Labour cost for kiln making(if

							any)
							How much does it cost to maintain the kiln per year? ______________ Ksh/Tsh

NB: For Improved Basic Earth Kiln (IBEK)

How many times the chimney is used before it must be replaced? _______________

Where is the old chimney taken to? ____

14. How much land does the kiln occupy? (Size of the kiln) ______________________________
15. What was the land used for before the kiln was established here?
    Annual crop
    Forest land
    Idle land
    Others: Specify ____
16. How much wood do you use to produce charcoal per production cycle? ___________________
17. Do you use specific species of wood for charcoal production? Yes ☐ No ☐
18. If yes which species and part of the tree do you use to produce charcoal?

Local name	Part of tree used (trunk, branches, whole tree….)	Reason for using these species, parts…

For every cycle of charcoal production, do you use single species or mixed tree species? Comment in the space provided Reason:

19. How do you transport the wood to the charcoal production site (if kiln is away from wood harvesting site)?

Transport mode used (earth/tarmac road etc)		Any additional comment (if any)
Means of transport used (truck, bicycle, etc)		
Distance covered (km) State from where also		

20. How much charcoal do you produce per cycle (e.g. using 90kg bag, how many bags per production)?
    ____
21. Is there water used during charcoal production?
    Yes ☐ No ☐
22. If yes, what is the source of the water used? ______________________________________
23. What is the amount of water used __________________ (liters)
24. Are there any waste products during the charcoal production process? Name them & their quantity in kg
    ____
25. What are the wastes used for /what happens to the wastes?
    ____
26. What do you use to package the charcoal you produce?
    ____

Section D: Charcoal transport

27. Where is the charcoal produced here transported to? Indicate in the table

	Market 1 name:_______________________	**Market 2 name:______________**	**Market 3 name:_______________**
Distance(km)			
Cost of transport			
Transport vehicle used to ferry charcoal			
Size of bag			

28. How much is charcoal sold at?

	Unit of sale	**Price per unit**	**Comments**
Individual consumers			
Retail traders			
Wholesale traders			

29. What are the labour requirements for charcoal production?

Activity	**No of days/hrs**	**Cost (where applicable)**	**Who: women/men**	**Comment**
Wood harvesting				
Wood drying				

Kiln construction				
Kiln loading with wood				
Carbonization process				
Cooling				
Sorting				
Packaging				
Others:				

30. Are you interested and willing to answer more questions in future?

Yes ☐ No ☐

Any additional comments (if any)

31. Who else is producing charcoal within the area? (Their name and location)

Thank you!!

Farm Residues production-Small enterprises **Questionnaire number: ____________**

Introduction

1. Introduce yourself to the respondents.
2. Tell the respondent where you come from (affiliation) and the purpose of your visit
3. Tell the respondent briefly what the project is about
4. The study aims to evaluate the environmental impacts and economic viability of different value chains for biomass energy.
5. Results from this study will help in policy and decision making in matters concerning biomass energy.
6. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions.
7. Inform the respondent about the duration of the interview (approx. 45 minutes)
8. Inform the respondent on the confidentiality of the questionnaire.
9. Ask the respondent if he/she has any questions.
10. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS.

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name of farm residues producer	
Gender	Male ☐ Female ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:______ Latitude:_____ Altitude:_________

Section B: Technology details

1. Do you currently use any farm residues to make/produce fuel?
   Yes ☐ No ☐
2. When did you start using farm residues to make fuel? ________ (year)
3. Which technologies do you use to make the fuel from farm residues? NB: Take photo of the technology (ies) in use if possible
4. What is the life span of the technology (ies)?
5. Technology acquisition?

Where was technology acquired from?	Cost of acquiring technology (Ksh)	Transport mode used (road, rail etc.)	Means of transport used (passenger car, bus etc)	Distance (km)

6. How often do you repair the technology you are using per year? ________________
7. How much does it cost you to do repairs and maintenance of the technology per year? _________ Ksh

Section C: Farm residues collection and processing

8. Fill in the table

			Cost per unit (where shaded)
a	Name farm residue used		
b	Source of farm residue (If bought include buying price/unit)		▨
c	Quantity of residue collected (kg/day)		
d	Transport mode (earth road, tarmac, rail etc)		
e	Transport vehicle used (passenger car, bicycle, truck etc)		
f	Distance covered to collect (km)		
g	Quantity of farm residue used (kg/ production cycle)		
h	Water (L/production cycle)		▨
i	Source of water used		

j	Any other material used (kg/production cycle) (Name it)		
K			
L	Electricity consumed (kWh/production cycle) (If using electrified machine)		
M	Fuel yield (kg/production cycle)		

9. For how much is the fuel produced from farm residues sold?

	Price per unit (kg)
When bought by local individual consumers	
Wholesalers	
Retailers	

10. Are you interested and willing to answer more questions in future?

Yes ☐ No ☐

Any additional comments

11. Who else is producing fuel from farm residues within the area? (Their name and location)

Thank You!!

Jatropha oil processor-small enterprises Questionnaire number: ______

Introduction

1. Introduce yourself to the respondents.
2. Tell the respondent where you come from (affiliation) and what the purpose of your visit
3. Tell the respondent briefly what the project is about:
4. The study aims to evaluate the environmental impacts and economic viability of different value chains for biomass energy. Results from this study will help in policy and decision making in matters concerning biomass energy.
5. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions.
6. Inform the respondent about the duration of the interview (approx. 45 minutes)
7. Inform the respondent on the confidentiality of the questionnaire.
8. Ask the respondent if he/she has any questions.
9. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS.

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name of biogas producer	
Gender	Male ☐ Female ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:______ Latitude:_____ Altitude:__________

Section B: Technology details

1. Which Jatropha oil extraction technology are you using? _________ NB: Take a photo of the technology
2. How much did the technology cost (buying price)
3. Where was the technology sourced from? Indicate in the table

Source of machine	Transport mode used	Transport vehicle used	Distance covered (km)

4. What is the lifespan of the technology in use? ____________________
5. After what period do you replace/ repair the oil extraction technology parts? (Tick in the appropriate box)

	Repair period & cost	Replacement period & cost
a. ___________		
Cost		
b. ___________		
Cost		
c. ___________		
Cost		
d. ____________		
Cost		

Section C: Oil processing

6. Do you use the oil extractor alone or is it shared among other households in the village?
   Used by individual ☐
   Shared among community members ☐
7. Transport of dried jatropha seeds to crusher

Transport mode used (earth road/tarmac road, rail etc)	
Type of vehicle used (passenger car, truck etc)	
Distance covered (km)	

8. Drying and storage of jatropha seeds & dehusking; please fill in the table below

Drying and dehusking method used (describe the method used for drying and dehusking of the jatropha seeds)	

Electricity used for this stage (kWh)	
Describe the type of facility used for storing the seeds before processing	

9. Oil extraction from jatropha seeds; Please fill in the table below: NB: Fill the un-shaded part for costs

Parameter	**Unit**	**Quantity**	**Cost/unit**
Dry Jatropha seeds	Kg		
Oil yield	L/kg seeds		
Electricity	Kwh/kg oil		
Water	l/kg		
Amount of co-products			
Husks	Kg/kg seeds		
Shells	Kg/kg seeds		
Seedcake	Kg/kg seeds		
Fatty acids	Kg/kg seeds		
Others ________________	Kg/kg		

10. What are the labour costs involved during?

	Cost (Ksh/Tsh)/unit	Time required (minutes, hrs/unit)
a. De-husking		
b. Pressing		
c. Filtering		
d. Packaging		

Section D: Co-products

11. What are the co-products used for?

Name of co-product	Use (s)	Replacing what?	Machinery involved	Transport distance	Transport mode	Transport vehicle	Distance (km)
Husks							
Shells							
Seedcake							
Fatty acids							
Other							

12. For how much is the jatropha oil and its co-products sold for?

Product	Where sold	To: (individuals/ retailers/wholesalers)	Unit	Price/unit	Transport method used	Distance (km)	Transport cost
Oil/fuel							
Fertilizer							
Soap							
Others							

13. Are you interested and willing to answer more questions in future?
Yes ☐ No ☐

Any additional comments

14. Who else is producing jatropha oil within the area? (Their name, mobile phone number and location)

Thank You!!

Jatropha Seed production Questionnaire number: _____

NB: Only seeds from hedges are considered for this study

Introduction

1. Introduce yourself to the respondents.
2. Tell the respondent where you come from (affiliation) and what the purpose of your visit
3. Tell the respondent briefly what the project is about:
4. The study aims to evaluate the environmental impacts and economic viability of different value chains for biomass energy. Results from this study will help in policy and decision making in matters concerning biomass energy.
5. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions.
6. Inform the respondent about the duration of the interview (approx. 45 minutes)
7. Inform the respondent on the confidentiality of the questionnaire.
8. Ask the respondent if he/she has any questions.
9. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS.

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name of respondent	
Gender	Male ☐ Female ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:______ Latitude:_____ Altitude:__________

Section B: Jatropha hedge establishment and seed production

1. What did you use to establish the jatropha hedge?

	Quantity	Cost per unit (Ksh)	Source
a. Seeds ☐	___________kg/m	________ Ksh/kg	
b. Cuttings ☐	___________Number of cuttings/m	________Ksh/cutting	
c. Seedlings ☐	___________Number of seedlings/m	________Ksh/seedling	

2. Any transport used to bring the seeds/cuttings/seedlings for jatropha hedge establishment

   Yes ☐ No ☐

3. If yes, please fill in the table

Transport mode used (earth road, tarmac road, rail etc)	
Type of vehicle used (passenger car, bicycle etc)	
Distance covered (km)	
Transport cost (Ksh)	

4. Length of pure jatropha hedge on your land (current hedge)_________________ (m) NB: Take photo of hedge
5. What is the lifespan of the hedge (How long does the jatropha hedge last)_________________ (years)
6. For how long has this hedge been here (when was it established)? ______________________
7. What is the cost of producing jatropha seeds from the jatropha hedge?

Steps	Ksh	Time needed
Hedge establishment –seeds/cuttings/seedlings		
Labour for hedge establishment		
Pruning the hedge		
Picking seeds		
Drying the seeds		

8. What was on the hedge before the jatropha hedge was established? __________________________________

9. What were the uses of the other hedge that was here previously before the jatropha hedge was established?
   Fodder for livestock ☐
   Medicinal plant ☐
   Organic manure for farms ☐
   Firewood ☐
   Others: Specify ____
10. How much jatropha seeds are produced by the hedge ________________ (kg/m/year)
11. Do you use any fertilizer on the hedge?
    Yes ☐ No ☐
12. If yes, which fertilizer ________________, amount________________ (kg/m), cost per kg________ (Ksh/kg)
13. Any other chemicals used ______________________ and amount ________ (kg/m), Cost per kg_______________ (Ksh/kg)
14. Is there any machinery used for hedge establishment
    Yes ☐ No ☐
15. If yes, which one? ____________________________ (Take photo)
16. Cost of the machine? _________________________
17. Are you interested and willing to answer more questions in future?
    Yes ☐ No ☐

Any additional comments

Who else has a Jatropha fence within this area? (Their name, mobile phone number and location)

Thank You!!

Household questionnaire **Questionnaire number: ______________________________**

Introduction

1. Introduce yourself to the respondents.
2. Tell the respondent where you come from (affiliation) and what the purpose of your visit
3. Tell the respondent briefly what the project is about:
4. The study aims to evaluate the environmental effects and the economic viability of different biomass energy technologies used for cooking. Results from this study will guide policy making for development of the country.
5. Ask for permission to carry out interview and ask the respondent if he/she has time to answer your questions.
6. Inform the respondent about the duration of the interview (approx. 25-30 minutes)
7. Inform the respondent on the confidentiality of the questionnaire.
8. Ask the respondent if he/she has any questions.
9. Make it clear that you are not providing assistance. DO NOT RAISE EXPECTATIONS

Section A: General Information

Enumerator's Name	
Date & time of interview	_ _ /_ _ / 2015 Time:
Name household head	
Name of respondent	
Gender of respondent	Male: ☐ Female: ☐
Mobile phone number	
County	
Sub-county	
Ward	
Village	
GPS Reading	Longitude:_______ Latitude:__________ Altitude:_______

Section B: Energy information

1. What is your source of energy for cooking?

Electricity ☐ Charcoal ☐ LPG ☐ Jatropha oil ☐ Biogas ☐
Fire wood ☐ Farm residues ☐

2. Where do you get your biomass fuel from?

Fuel type	**Where do you get your fuel from**	**Distance (km)**	**Transport mode & vehicle type used where applicable**
Charcoal			
Jatropha oil			
Biogas			
Farm residues (briquettes)			
Firewood	*Go to question 3 below for those that use firewood*		

3. Source of the firewood
Collect dead wood from forest ☐
Cut trees from natural forest ☐
Trees between crops ☐
Own plantation ☐
Others ☐

Please specify ____

4. Do you use any machine to harvest the wood for firewood?
   Yes ☐ No ☐
5. If yes, which machine to you use for firewood harvesting? ___________
6. Are the trees only used for firewood? Yes ☐ No ☐
7. If no, what are the other uses of the trees? ___________________
8. If trees are cut for firewood, what is the land used for afterwards?
   ____
9. How much time do you use to collect one head load of firewood? _________ Hours

Stove information

NB: *Take photo of stove(s) in use by the household*

10. Fill in the table for stove information

Fuel type	Type of stove present/in use	How much was it?	Where did you buy stove?	Transport used to acquire stove (mode, type)	Distance (km)	How long does the stove last	After what period is it repaired?	Repair cost Ksh/Tsh
Charcoal	1.							
	2.							
Jatropha oil	1.							
	2.							
Biogas	1.							
	2.							
Farm residues	1.							
	2.							
Firewood	1.							
	2.							

11. How much fuel and time do you use to cook (Please not the unit bought e.g. 90kg bag etc and how long the fuel lasts)

Stove(s) in use	Meals cooked/day (name food items)	Time used to cook/day (minutes, hrs)
1.	Breakfast:	
	Lunch:	

	Dinner/supper:	
2.	Breakfast:	
	Lunch:	
	Dinner/supper:	
3.	Breakfast:	
	Lunch:	
	Dinner/supper:	

12. How much fuel do you use per month?

Stove (s)	Amount of fuel used per month	Cost per unit (Ksh/Tsh)

13. What challenges do you face when using the stove(s)?

Name of stove: ______________________________

Challenge(s) faced:

____

Name of stove:

____

Challenge(s) faced______________________________

14. Are you interested and willing to answer more questions in future?

Yes ☐ No ☐

Any additional comments

15. Who else is using the same type of stove in this area? (Their name, mobile phone number and location)

____

Thank You!!

Appendix 2: Expert opinion interview guides

Biogas-Renewable energy centre, Kitui & Musekavo CFA

1. Digester specifications
2. Source of technology/materials for making digester
3. Efficiency (conversion rate) of technology
4. Is the biogas volume dependent on digester type? If yes which one has a higher efficiency?
5. Feedstock requirement
    a. What type of feedstock can be used for biogas generation
    b. Amount of feedstock needed for sufficient biogas production
    c. Preparation procedure and ratio of feedstock e.g. dung: water needed for different technologies
6. Amount of biogas generated (volume of digester, m^3)
7. Biogas needed to cook a warm meal(amount of biogas generated, m^3)
8. Livestock number for sufficient dung/feedstock production per day
9. Does the livestock (e.g. cows, goats, chicken etc) type affect the quality of feedstock and why?
10. Does the age of the livestock affect quality of the feedstock & digestate?
11. Does the livestock feed affect the quality of the feedstock & digestate?
12. Is the digestate sufficient to improve crop productivity i.e. does one need to supplement with organic fertilizer e.g. CAN for top dressing in Kitui Central
13. How much digestate can be used in 1 acre land for improved crop productivity?
14. Which feedstock is suitable/mostly preferred for biogas production?
15. Is there any other type of feedstock that can be used for biogas generation in Kitui Central? Which one(s)
16. Cost of installation of digester(materials & labour)
17. Cost of operation & maintenance of digester
18. Replacement period/lifespan of digester

Farm residues, Musekavo CFA

Manual press-(technology specifications)

1. What residues can be used?
2. What amount of raw materials (each raw material used) is required per production cycle?
3. How much briquettes is produced (kg) per cycle
4. Cost of purchasing technology
5. Source (where was it bought)
6. Cost of operating the technology
7. Frequency of repair of the technology
8. Which parts are repaired and at what intervals/periods
9. Maintenance costs of machine
10. Replacement period/lifespan of manual press

Charcoal/firewood-KFS/conservator/Forester/TFS

1. Volume of wood needed to produce?? amount of charcoal for the different kilns
2. Estimation of tree volume (e.g. a mature tree)
3. Common tree species for charcoal making in Kitui and reason?
4. Is there a specific part of the tree used for charcoal production?
5. Which areas are permitted for charcoal production?
6. Are there current charcoal regulations/restrictions
7. Where is the main market for charcoal produced?
8. Is there competition between wood for charcoal/firewood with other uses? Which ones?
9. Are there any notable environmental consequences of charcoal production? Which areas?
10. Are there any tree species or trees from a certain area which cannot be used by the community for charcoal making or firewood? Which trees, area and why is that so?
11. Any afforestation activities by community members?
12. How does the forest department support these communities?
13. True weight of charcoal in a 90kg capacity bag
14. True weight of charcoal in a debe
15. Which are common tree species for firewood? Reason for their use?

Stoves-NGOs

1. What is the stove efficiency?
2. Stove specifications (materials required to make stove, their source etc)
3. Cost of purchasing/installation (materials, transportation & labour)
4. Cost of maintenance (repair etc)- which part is repaired/replaced
5. Frequency of repair of the stove/cooking device
6. Cost of repair (cost of spare parts-which parts, labour costs)
7. Replacement period/lifespan of stove
8. How much fuel is needed to make a meal for the different stoves (Fuel consumption for a warm meal)?
9. Time needed to make the meal (name the meal) (hours, minutes)
    a. Rocket -Caritus
    b. Envirofit -KREP/FSA
    c. Maendeleo -Renewable energy center/MUSEKAVO
    d. KCJ -Renewable energy center/MUSEKAVO
    e. Biogas burner -Renewable energy center/MUSEKAVO
    f. Okoa/kuni-chache/VACVINA Biogas digester-TaTEDO
10. Adoption rate (how is its reception in general in Kitui Central)?
11. Why is it being promoted?
12. What are the challenges faced in its promotion (challenges faced so far)?
13. Challenges of its use
14. Its advantages
15. Which other technologies are you promoting?

RESEARCH OUTPUT

Peer Reviewed Journal Articles

i. **Okoko, A**. et al., 2017. The carbon footprints of alternative value chains for biomass energy for cooking in Kenya and Tanzania. *Sustainable Energy Technologies Assessment,* Volume 22, pp. 124-133.

ii. **Okoko, A.** et al., 2018. Life cycle costing of alternative value chains for biomass energy for cooking in Kenya and Tanzania. *Journal of Renewable Energy*, Volume 2018, pp. 1-12

Policy Briefs

i. Ehrensperger A, Gatimu J, Willi S, Kitala JK, **Okoko A**, Shuma J, Sago S, Kiteme B, Wymann von Dach S. 2017. *What future for cooking with solid biomass? The benefits of improved stoves and micro-gasifiers*. ProBE Policy Brief 1. Nairobi, Kenya and Bern, Switzerland

ii. Reinhard J, Bär R, **Okoko A**, Willi S, Zah R, Ehrensperger A, Wymann von Dach S, Kiteme B. 2017. *More out of less: future scenarios of clean cooking solutions in East Africa*. ProBE Policy Brief 2. Nanyuki, Kenya and Bern, Switzerland.

iii. Ehrensperger A, Wymann von Dach S, Bär R, **Okoko A**, Lannen A. 2018. *A Burning Challenge: Making Biomass Cooking Fuels Sustainable in East Africa.* CDE Policy Brief, No. 13. Bern, Switzerland: CDE