UNIVERSITY OF NAPLES FEDERICO II

DEPARTMENT OF AGRICULTURE

RESEARCH DOCTORATE IN

IMPROVEMENT AND MANAGEMENT OF AGRICULTURAL AND FOREST RESOURCES

XXVI CYCLE

ASSESSING SUSTAINABILITY OF BIOENERGY SYSTEMS IN DEVELOPING COUNTRIES: METHODOLOGICAL DEVELOPMENT AND APPLICATION

Thesis submitted to Department of Agriculture in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy of the University of Naples Federico II

Collins OKELLO

(MSc Agric. Eng.)

Tutor:	Prof. Lorenzo Boccia
Coordinator:	Prof. Guido D’Urso

PORTICI, MARCH 2014

Acknowledgements

This study was carried out with the aim of improving decision making process to aid transition from traditional biomass to modern energy for cooking in developing countries. It was a very broad and challenging study that would not be possible without the support of several institutions and individuals. I would like to sincerely acknowledge all the support rendered to me during the study. First, I extend my sincerely acknowledgements to the University Naples Federico II for funding the PhD programme and to my employer, Gulu University, which provided the steppingstone leading to this study. I extend my sincere appreciation to the top management of Gulu University especially Prof. J.H. Nyeko Pen-Mogi and Prof. Callistus Baliddawa for their guidance and support. I also extend my sincere acknowledgements to GuluNap project for providing a platform on which this study was initiated. Special thanks to Prof. Guido D'Urso for his coordination of the project that has resulted in this thesis. As the coordinator of the PhD programme, Prof. Guido D'Urso also played a very important role of overseeing the progress of the study and offered me a lot of guidance and encouragement over the last three years.

The supervision of Prof. Lorenzo Boccia was very essential in accomplishing this study and I sincerely acknowledge. I sincerely thank him for the continued encouragement and guidance throughout the study. I also extend acknowledgements to Prof. Salvatore Faugno and Prof. Stefania Pindozzi for the support and very helpful suggestions on the thesis. Special acknowledgements all my colleagues in the laboratory of Ecological Engineering and Topography; specifically to Luca Ardito, Alessandra Capolupo, Elena Cervelli, Maura Sannino, Felicia Rugari, Roberta Infascelli, Francesca Audino, Maria Buglione and Assunta Giglio. Thank you for the all kind of support, encouragement and team spirit exhibited during the study period. Special acknowledgements to Prof. Angelo Fierro, Dr. Amalia Zucaro and Dr. Annachiara Forte of the Department of Biology, for the useful discussions on the life cycle assessment aspects of this study.

This study also benefited from guidance of several scholars I came into contact with during various summer schools I attended. I extend sincere acknowledgements to Dr. Raffaele Spinelli of CNR-IVALSA in Florence for very useful pieces of advices on of aspects scientific writing. I also learnt a lot from Dr. Davide Geneletti of the University of Trento, especially on multi-criteria analysis, and Blal Adem Esmail with whom we shared a lot of useful information. Appreciations to Prof. Stefania Massari, of the University of Salento for the training on life cycle assessment. Special appreciation to the management of the Research Centre on Appropriate Technologies for Environmental Management in Developing Countries (CeTAmb) at the University of Brescia for training I received; especially, on multi-criteria analysis and sustainability assessment.

I also would like to extend my sincere acknowledgements to management and staff of the Faculty of Agriculture and Environment of Gulu University for the support rendered to me, especially during the stakeholder workshop. Special appreciations to the Dean of the Faculty Dr. Duncan Ongeng for providing the facilities for the workshop, and to Dr. Martine Nyeko, Walter Odongo and Eng. Benedict Ebangu for accepting to facilitate the stakeholder workshop. Special thanks to Prof. Marion Okot, Joachim Bongomin, Geoffrey Openy and Martin Odoch for their contributions in organising the workshop. Appreciations to all the participants of the workshop; due to lack of space, I can only mention Dr. Tony Kidega of Gulu Uganda Country Dairy Project, Wilfred Okech of Heifer International and Bosco Lakoch of Mission for Rural Transformation Uganda. I also express my sincerely acknowledgements to Dr. Grace Okiror for the technical assistance with reference management and to Emmanuel Menya for proof reading the thesis.

I also extend special acknowledgements to friends especially Alessandro Mataffo and John Leslie Fultz for the company, support and encouragement. Giovanni Berti for introducing me to biogas energy installations in Italy, and for joint voluntary activities we are conducting. I also convey special appreciation to Dr. Peter Olupot for all the encouragements and support.

Lastly, I extend my special appreciation to members of my family for all the support and taking care of home while I was away, most especially my late dad, Nekemia Obwoyo Laker, mother Jenti Obwoyo, wife Jane, my sister Betty and brothers Robinson, Denis, Michael and Peter and cousin Patrick Olweny. I extend my special appreciation to Jane, for patiently taking care of Tobiah and Jonathan during the three-year period while I was away. I dedicate this work to you, and to Tobiah and Jonathan, that they may grow up with the desire to study.

There are many other individual and institutions that contributed generously to this study, but due to lack of space I cannot mention all of them. My the almighty God who meticulously guided me through course of this study reward abundantly!

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List of Abbreviations

AHP	Analytic Hierarchy Process
CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CAN	Calcium Ammonium Nitrate Fertilizer
CBA	Cost-Benefit Analysis
CDO	Cotton Development Organisation
CHP	Combined Heat and Power
DALY	Disability Adjusted Life Years
DM	Dry Matter
EC-RED	European Commission Renewable Energy Directive
EF	Ecological Footprint
EIA	Environmental Impact Assessment
ELECTRE	Elimination and Choice Expressing Reality
EPA	Environmental Protection Agency of the United States of America
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
GACC	Global Alliance of Clean Cookstoves
GAIA	Graphical Analysis for Interactive Aid
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographical Information Systems
GTZ	German Development Organisation
HDM	Hierarchical Decision Model
HHV	Higher Heating Value
IAP	Indoor Air Pollution
IEA	International Energy Agency
IRR	Internal Rate of Return
ISO	International Organisation for Standardisation
KCJ	Kenya Ceramic Jiko
KCL	Muriate Potash fertilizer
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MAAIF	Ministry of Agriculture Animal Industry and Fisheries
MCA	Multi-criteria Analysis

MCDA	Multi-criteria Decision Analysis
MDGs	Millennium Development Goals
MEMD	Ministry of Energy and Mineral Development
MFA	Material Flow Analysis
MFP	Multi-functional Platforms
mPt	milli-Points
NARO	National Agricultural Research Organisation
NEMA	National Environment Management Authority
NIMBY	Not In My Backyard
NMVOC	Non Methane Volatile Organic Compounds
PAF	Potentially Affected Fraction
PCA	Principal Component Analysis
PDF	Potentially Disappeared Fraction
PROMETHEE	Preference Ranking and Organisational Method for Enhanced Evaluation
PV	Photovoltaic
RPR	Residue to Product Ratio
SETAC	Society of Environmental Toxicology and Chemistry
SNV	Netherlands Development Organisation
SSA	Sub-Saharan Africa
SSP	Single Superphosphate Fertilizer
SWOT	Strengths, Weaknesses, Opportunities and Threats
TBL	Triple Bottom Line
TLUD	Top-lit Updraft
TOE	Tonnes Oil Equivalent
TSP	Tipple Superphosphate Fertilizer
UBOS	Uganda Bureau of Standards
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
USA	United States of America
USCTA	Uganda Sugarcane Technologists Association
USD	United States Dollar
WHO	World Health Organisation
WSI	Weight Stability Interval

Abstract

Close to a half of the global population is currently deprived of clean and reliable energy for cooking. Majority of the energy poor live in developing countries where use of traditional biomass is prevalent and associated with several social, economic, environmental and technological challenges. Recently, United Nations General Assembly emphasised the importance of access to sustainable energy to all, most especially in developing countries. It noted that access to clean and reliable energy is critical to meeting the millennium development goals and ensuring sustainable development. This suggests the need for more efforts to incorporate sustainability concerns in planning energy systems in developing countries. This could lead to the identification of more sustainable technologies for cooking, and also provides benchmarks to help monitor progress towards sustainable development of energy systems. To achieve these objectives, availability of suitable tools to help policy and decision makers in selecting energy systems in developing countries would be very critical. However, planning for sustainability is a very intricate endeavour and presents a knowledge gap especially in developing countries where it is a relatively new concept. This study was therefore carried out with the aim of developing an appropriate sustainability assessment method for selecting bioenergy systems for cooking in developing countries.

The proposed sustainability assessment framework is an integrated method that incorporates the social, economic, environmental and technological concerns of biomass energy systems to aid decision making. It is based on multi-criteria decision analysis as a tool to aid participatory ranking and selection of biomass energy systems to ensure sustainability. The framework provides for participatory appraisal of a finite set of energy alternatives at the beginning of the assessment so as to identify and eliminate options that are obviously unacceptable by stakeholders. Methods for selection, ranking and evaluation of sustainability criteria were proposed. A model based on Preference Ranking and Organisational Method for Enhanced Evaluation (PROMETHEE) and Graphical Analysis for Interactive Aid (GAIA), was proposed as a tool for final ranking of biomass cooking technologies on the basis of a set of sustainability criteria. The methodology was applied in Uganda to rank domestic biogas, briquette gasification and Jatropha plant oil cooking energy systems with charcoal system as the reference.

Participatory appraisal of the energy systems resulted in Jatropha oil system as the best cooking energy system according to Ugandan stakeholders. It was followed by biogas and briquette while charcoal, ranked last. A set of 21 criteria for assessing sustainability bioenergy systems was developed under Ugandan conditions and weights assigned to them by a multi-stakeholder panel using the analytic hierarchy process. Economic criteria were ranked as most important considerations influencing sustainability of bioenergy systems in the country, while technical criteria generally ranked lowest. Results of environmental assessment of the energy systems indicated that biogas is the most environmentally sustainable alternative, while charcoal was the worst option. The environmental performances of biogas and Jatropha systems were observed to significantly improve with recycling of waste products as fertilizer. Results of multi-criteria sustainability assessment showed that under the business as usual scenario, charcoal and biogas were incomparable under PROMETHEE I partial ranking, but better than Jatropha and briquette gasification systems, which were also found to be incomparable. Biogas was ranked as the best alternative under PROMETHEE II complete ranking, while Jatropha and briquette systems performed worse than charcoal. Biogas systems was again ranked as the best alternative when by-products were recycled as fertilizer. It was followed by Jatropha and briquette systems, which performed worse than charcoal. The study further showed that the charcoal cooking is inefficient and pose high health risks to users compared to the other three energy alternatives.

In summary, the study showed that economic factors play a predominant role in the decisions by households to adopt more sustainable bioenergy technologies for cooking in Uganda. Also, the environmental performance of biogas and Jatropha energy systems significantly improve with increase in recycling of by-products as fertilizers, and avoidance of open air burning of residues. Recycling of by-products significantly improves overall sustainability of biogas and Jatropha bioenergy systems. Biogas energy system seems to be the most sustainable energy system for cooking in Uganda. The study further showed that the proposed method for participatory appraisal of bioenergy systems, based on strengths, weaknesses, opportunities and threats; analytic hierarchy process, and desirability functions seem to be a very promising tool. In conclusion, the proposed multi-criteria sustainability assessment framework showed a high potential to be used as a tool to aid decision-making when selecting cooking energy systems in developing countries.

Abstract – Italian version

Circa metà della popolazione mondiale è attualmente priva di energia pulita e sicura da utilizzare per la cottura dei cibi. La maggior parte di questa risiede nei paesi in via di sviluppo, dove l'uso delle biomasse tradizionali è prevalente e pone problemi sociali, economici, ambientali e tecnologici. Recentemente, l'Assemblea Generale delle Nazioni Unite ha sottolineato la necessità, per questi paesi, di poter accedere all'energia sostenibile, in quanto tale accesso è fondamentale per raggiungere gli obiettivi futuri di crescita e di sviluppo sostenibile. Tutto ciò suggerisce la necessità di integrare nella progettazione dei sistemi energetici anche aspetti di sostenibilità volti a individuare tecnologie più sostenibili per la cottura degli alimenti e fornire anche dei punti di riferimento per monitorare i progressi verso lo sviluppo sostenibile dei sistemi energetici. A tal fine si rende necessaria l'individuazione e l'offerta di strumenti adeguati di supporto ai soggetti politici e decisionali, affinché sia possibile l'implementazione degli stessi sistemi energetici. La pianificazione degli interventi per la sostenibilità rappresenta, quindi, un grande sforzo che necessita il superamento di un notevole gap di conoscenza, soprattutto nei paesi in via di sviluppo in cui tale argomento è un concetto relativamente nuovo. Questo studio è stato quindi effettuato con l'obiettivo di sviluppare un metodo appropriato di valutazione della sostenibilità per la selezione dei sistemi bioenergetici nei paesi in via di sviluppo.

Il *framework* di valutazione della sostenibilità proposto è un metodo integrato che incorpora i problemi sociali, economici, ambientali e tecnologici dei sistemi energetici a biomassa per facilitare il processo decisionale. Lo stesso si basa su analisi decisionali multi-criterio per consentire, attraverso un "metodo partecipatorio", la selezione di sistemi energetici a biomassa che garantiscano la sostenibilità. Il quadro decisionale prevede la valutazione partecipativa di un insieme finito di alternative energetiche nelle fasi preliminari di implementazione, al fine di individuare ed eliminare quelle inaccettabili dalle parti interessate. Pertanto vengono proposti dei metodi dettagliati per la selezione, l'assegnazione di priorità e la valutazione dei criteri di sostenibilità. I metodi di analisi multicriterio proposti sono basati sul *Preference Ranking and Organisational Method for Enhanced Evaluation* (PROMETHEE) e sul *Graphical Analysis for Interactive Aid* (GAIA). Questi vengono adottati per l'assegnazione delle priorità di sostenibilità ad una serie di tecnologie di cottura degli alimenti con l'uso di biomassa. La metodologia è stata applicata in Uganda, dove sono stati comparati differenti sistemi di

cottura a biomasse con il sistema a carbone. I sistemi confrontati sono: il biogas domestico, le *briquette* per la gassificazione e i sistemi di cottura energetici ad olio vegetale di Jatropha.

Gli *stakeholders* ugandesi, attraverso la valutazione partecipativa, hanno assegnato un punteggio più alto al sistema energetico di cottura alimentato ad olio di Jatropha, che è quindi stato classificato come il miglior sistema. Seguono nella classifica il biogas e le *briquette,* mentre il carbone si è posizionato all'ultimo posto. Allo scopo sono stati sviluppati una serie di criteri di sostenibilità per i sistemi bioenergetici: in riferimento alle condizioni ugandesi sono stati assegnati valori diversi da un pannello *multi-stakeholder,* utilizzando *l'Analitic Hierarchy Process* (AHP). I criteri economici sono stati classificati come i più importanti tra le considerazioni di cui tener conto nel confronto dei sistemi bioenergetici sostenibili nel paese. Invece, i criteri tecnici sono stati classificati come ultimi. I risultati della valutazione ambientale dei sistemi energetici hanno indicato il biogas come l'alternativa più sostenibile per l'ambiente, mentre il carbone è risultato essere il peggiore.

È stato inoltre osservato che le prestazioni ambientali del biogas e dei sistemi con olio di Jatropha migliorano in modo significativo quando accoppiati, con successivo riutilizzo dei prodotti di scarto come fertilizzante in agricoltura. I risultati della valutazione di sostenibilità multi-criterio hanno dimostrato che da un punto di vista del *business,* come scenario immutato, il carbone di legna e il biogas non sono confrontabili con il ranking parziale di PROMETHEE I. Anche l'olio di Jatropha e i sistemi di gassificazione con *briquette* si sono dimostrati altrettanto inconfrontabili. Il biogas è stato classificato come la migliore alternativa con il ranking totale di PROMETHEE II, mentre la Jatropha e le *briquette* hanno mostrato *performance* peggiori rispetto al sistema di riferimento. Quando si è ipotizzato di riciclare come fertilizzante i sottoprodotti, i sistemi a biogas si sono ancora una volta classificati come la migliore alternativa, seguiti da Jatropha e, in ultimo, dalle *briquette,* classificate come peggiori anche rispetto al carbone. Lo studio ha inoltre dimostrato che il carbone utilizzato per la cottura degli alimenti in Uganda è inefficiente e pone elevati rischi per la salute degli utenti rispetto alle tre alternative considerate.

In generale lo studio ha mostrato che, in Uganda, i fattori economici giocano un ruolo preponderante nella decisione delle famiglie di adottare tecnologie bioenergetiche migliori per cucinare. Inoltre, è stato dimostrato che le prestazioni ambientali del biogas e dei sistemi energetici con olio di Jatropha migliorano significativamente se si aumenta il riciclaggio dei prodotti di scarto, come fertilizzanti, e se si evita la combustione in ambiente aperto dei residui. Il riciclaggio dei sottoprodotti migliora in modo significativo la sostenibilità complessiva del biogas e dei sistemi bioenergetici con olio di Jatropha. Il sistema energetico con biogas sembra risultare quello più sostenibile per la cottura dei cibi in Uganda. Il metodo proposto per la valutazione partecipativa dei sistemi bioenergetici, basato sul confronto delle caratteristiche forza-debolezza e opportunità-minaccia, sull'AHP e sulle funzioni di desiderabilità, sembra essere uno strumento molto promettente. In conclusione, il quadro di valutazione di sostenibilità proposto, basato su analisi multi-criterio, ha mostrato un alto potenziale come strumento di supporto alle decisioni per la selezione dei sistemi di cottura degli alimenti più sostenibili per un paese in via di sviluppo.

PART I

In introduction and state of the art of bioenergy development and bio-residue resources in Uganda

Chapter 1 – Introduction

Summary

Currently, about 2.6 billion people use traditional biomass for cooking resulting in over 2 million premature deaths annually due to indoor air pollution. Traditional biomass use is also associated with a variety of social, economic and environmental challenges. Provision of clean and reliable energy for cooking in developing countries is therefore recognised as critical to sustainable development and attainment of the millennium development goals. This Chapter provides important background information that motivated this study. It provides an overview of the challenges facing the global energy supplies with a particular focus on developing countries, leading to the objectives of the study. The chapter also provides detailed information on the scope and general organisation and presentation of the thesis.

1.1 Background

1.1.1 Global energy outlook

Energy is an indispensable necessity of human kind. Basically, development of the world is largely dependent on the availability and access to clean, affordable and reliable energy. The growth and sustainability of all the major sectors of the modern economy such as industries, agriculture and services strongly depend on various forms of energy. The household sector requires energy for space heating to ensure comfort of occupants as well as for cooking and water heating. Currently, energy supplies are predominated by fossil fuels with an estimated share of 82% in the global energy mix (IEA, 2013). However, use of fossil fuels is faced by several challenges; for example, deposits are not uniformly distributed over the earth's surface, resulting in concerns of energy security of countries without the resource. Moreover, they are non-renewable; thus, threatened by depletion (Shafiee and Topal, 2009).

Fossil fuels are also the main source of greenhouse gases (GHG), which lead to global warming and ultimately climate change. Global climate change is one of the major development challenges of the modern era because of several risks it poses to the stability of our planet. Consequently, there are currently global commitments such as the United Nations Framework Convention on Climate Change (UNFCCC), which aims at stabilising anthropogenic GHG concentration in the atmosphere to levels that do not interfere with the global climate systems. The Kyoto Protocol in particular sets binding GHG emissions reduction targets for industrialised countries, though developing countries do not have set targets. These global commitments, coupled with the need to ensure energy security of nations have led to renewed interest in renewable energy.

A wide range of renewable energy sources are currently being explored as alternative to fossil fuels. Examples include solar, wind, biomass, hydropower, ocean and geothermal. Apart from being CO_2 neutral, renewable energy contributes to reduction of pollutants emissions, and promotes energy security. Others include creation of local employment and savings of foreign currency that could have been spent on importation of fossil fuels. However, renewable energy have generally had less competitive prices than fossil fuels, though this trend is observed to be reversing in recent past (Caspary, 2009). The contribution of renewable energy to the world's primary energy use in the year 2011 was estimated to be 13%, but was projected to reach 18% by 2035 (IEA, 2013). Biomass in woody form remains the world's single most important renewable energy source, contributing 9% of total primary energy demand and 65% of primary renewable energy consumption in the year 2010 (Lauri et al., 2013).

1.1.2 Overview of biomass and bioenergy

By definition, biomass is organic material of plant or animal origin. Bioenergy is energy derived from biomass materials such as wood fuels, herbaceous energy crops, vegetable oils, plant and animal residues (Mohammed et al., 2013). Biomass is an important source of energy, contributing about 18% of the global heat energy use in the year 2011. The building sector is the main user of biomass accounting for 65% of bioenergy used globally and 75% in developing countries (IEA, 2013). Interest in bioenergy and other renewable energy increased since the oil crisis of the 1970s. Biomass energy, in particular, has attracted a lot of research and development interests because of its flexibility to be processed into a variety of solid, liquid and gaseous fuels (Demirbas et al., 2009). This makes it possible for biomass to substitute fossil fuels in both stationary and mobile applications such as transport. When well-managed, bioenergy has a potential to be carbon neutral since the carbon dioxide emitted during combustion is reabsorbed by plant during photosynthesis. However, as noted by Zanchi et al., (2012) when the rate of biomass extraction exceeds growth rate, bioenergy systems could result in net GHG emissions to the atmosphere.

Energy from biomass can be broadly classified as *traditional* and *modern* biomass (Goldemberg and Teixeira Coelho, 2004). Modern biomass involves conversion of biomass from agricultural, forest and municipal residues into heat, electricity or transport fuels (Goldemberg, 2007). Provision of modern biomass energy is generally done sustainably, and the products are traded as commercial fuels, and are mainly used in industrialised countries. It includes second generation biofuels, derived from lignocellulosic biomass, using less conventional conversion routes (Eisentraut, 2010). Second generation biofuels are believed to be more sustainable than first generation biofuels derived from sugars and oils from arable crops, which could result in competition with food production. Traditional biomass on the other hand involves inefficient use of biomass as fuelwood and is generally considered unsustainable. It is the predominant source of energy for cooking and heating in developing countries. According to IEA (2012), traditional biomass use accounts for 59% of the global bioenergy use in the year 2011.

1.1.3 Bioenergy in the context of industrialised economies

It is estimated that biomass contributes 9 to 13% of the primary energy supplies of industrialised countries, and is the most widely used renewable energy source (Faaij, 2006). The challenge of climate change, coupled with commitments such as the UNFCCC and the Kyoto Protocol have resulted in a tremendous increase in the share of bioenergy in the energy mix of developed countries. Bioenergy utilisation in these countries is mainly through modern biomass, and aims at supplying energy requirements for industry, power generation and transport. Bioenergy development in the European Union (EU) is closely linked to climate change mitigation efforts, which aims at reducing GHG emissions, by substituting fossil fuels with biomass and other renewable energy sources. The main driving policy is European Commission Renewable Energy Directive (EC-RED), which sets targets for member states to achieve 20% reduction in GHG emissions by using 20% renewable energy by the year 2020 (European Commission, 2009).

The United States of America (USA) so far remains the world's leading producer of biofuels, mainly from corn and oil crops (Sorda et al., 2010). Like in the EU, bioenergy development efforts in USA aim at achieving significant increase of the share of biofuels in the transport sector. The US renewable fuel standards (USEPA, 2010) sets stringent targets aimed at increasing production of biofuels to 136 billion litres by the year 2022

(Goldemberg et al., 2014). The challenges with bioenergy development in developed industrial economies however hinges on the competitiveness of biofuels compared to fossil fuels. The challenge of competition with food production is being overcome by efforts to use second generation biofuels using cellulosic biomass. In most cases, developed countries have well developed policies aimed at promoting renewable energy use while minimised environmental and social impacts of development of the sector (Sorda et al., 2010).

1.1.4 Bioenergy in the context of emerging and developing economies

Energy profiles of developing countries is characterised by high levels of biomass energy use. Biomass contributes one-fifth to a third of primary energy use in developing countries. Considering developing countries as a whole, about 83% of the rural population use biomass for cooking, and this proportion is up to 90% in sub-Saharan Africa (SSA) (Kaygusuz, 2011). Unlike in industrialised countries that mainly use modern biomass, bioenergy use in developing countries is predominantly in traditional form.

However, there are a few examples of emerging economies like Brazil, India, China and Thailand, which have registered considerable research and development in modern biomass use including second generation biofuels (Eisentraut, 2010). Brazil is probably one of the best success stories of bioenergy development due to the ethanol programme, which has resulted in a significant share of biofuel use in its transport sector. The success of the Brazilian biofuel programme is mainly due to production of bio-ethanol from sugarcane. Current policies in Brazil require that all gasoline sold on the market is blended with 20 to 25% bio-ethanol (Balat and Balat, 2009). China recently developed the Renewable Energy Promotion Law of 2005, with the aim of increasing national energy supply from renewable sources (Cherni and Kentish, 2007). This is also leading to increased use of modern biomass in the country.

Generally, the bulk of biomass energy use in developing countries is predominantly in traditional form using inefficient technologies. Most of the biomass used in developing countries is solid fuels such as firewood, charcoal, crops residues and animal dung. Direct combustion of the biomass usually takes place in traditional stoves with very low efficiencies. Recent estimates by the IEA (2013), indicated that at least 2.6 billion people use traditional biomass for cooking and heating, most of them in Africa and Asia. This number is currently still increasing due lack of policies to promote use of modern biomass energy. Pachauri et al., (2013) estimated that the number of people using traditional fuels and stoves will increase by 50 to 220 million between 2005 and 2030, if favourable policies are not implemented. This trend needs to be reversed due to the sustainability challenges of traditional biomass use discussed in the following section.

1.2 Bioenergy and sustainability in developing countries

Bioenergy use in developing countries is faced with a number of sustainability challenges including severe impacts on human health and the environment, as well as gender and socio-economic issues. Use of traditional biomass for cooking and heating in developing countries often times takes place in poorly ventilated indoor environment. This results in high levels of indoor air pollution (IAP) caused by gases such as carbon monoxide (CO), particulates matter, and non-methane volatile organic compounds (NMVOC). Indoor air pollution is one of the major causes of premature death amongst children and adults in developing countries (Foell et al., 2011; Kaygusuz, 2012). It is associated with illnesses such as pneumonia, chronic obstructive pulmonary disease and lung cancer. It is also believed to cause asthma, cataracts, low birth weight and still birth, tuberculosis and lung cancer (Lim et al., 2013; Norma, 2011). Recent estimates indicate that every year, up to 2 million people die prematurely due to ailments caused by IAP (Martin et al., 2011; Norma, 2011). The most vulnerable population group are children and women who are the most exposed to the risk.

Possibility of wood fuel crisis due to depletion as a result of excessive harvesting was a major concern in the 1970s. However, since the 1990s, the scientific community has generally accepted that fuelwood use may not necessarily lead to deforestation, and that fuelwood crisis may not necessarily become a reality (Matsika et al., 2013). Nevertheless, intensive use of charcoal majorly in urban areas of SSA is known to have potential to lead to deforestation and forest degradation local scale (Foell et al., 2011; Mwampamba, 2007). This could result in reduction in soil fertility and lead to negative impacts on the general health of the ecosystem. Other impacts include reduction in soil infiltrations capacity and sedimentation of rivers (Butz, 2013). Therefore, energy supply from charcoal could result in negative impacts on the environment, with possible adverse consequences on the socio-economic status of the population of developing countries.

Traditional biomass use is also known to contribute significantly to the global climate change phenomenon due to emissions of GHGs such as nitrous oxides and methane. It is also known to contribute to about 18% of the global atmospheric black carbon concentration (Foell et al., 2011). Apart from contributing to global warming, black carbon is also known to increase melting of glaciers and impact regional rainfall and monsoons (Venkataraman et al., 2010).

Another major sustainability challenge with traditional biomass fuel use in developing countries is associated with social and gender dimensions. Women and children lose time, which could have been spent on more productive activities on biomass collection and processing. The collection process in particular is associated with considerable amount of human drudgery and time loss (Foell et al., 2011). This could result in serious social and economic challenges by excluding women from participating in social and economic development.

Though not specifically having a target in the millennium development goals (MDGs) access to clean and affordable energy has been identified as critical to achieving the MDGs. This is due to the benefits it renders, such as improved maternal health, reduction in premature death and environmental impacts, saving of time for fuelwood collection. Overall, improving access to clean energy for cooking is expected to contribute to achieving the MDGs, improve human welfare and contribute to sustainable development, most especially in developing countries (Haines et al., 2007). Consequently, there are a number of global and national efforts aimed at improving access to clean, reliable and efficient energy for cooling in developing countries.

1.3 Initiatives to improve sustainability of traditional biomass

The health and environmental challenges of traditional biomass use has attracted attention of the global community in the recent past. Concerns to reduce indoor air pollution and other environmental impacts of traditional biomass use have resulted in the formation of the Global Alliance for Clean Cookstoves (GACC), led by the United Nations Foundation (Smith, 2010). The GACC is a coalition of governmental, NGOs, private sector and civil society organisations with a common goal of scaling up use of improved cooking stoves in developing countries. The stoves promoted are affordable, acceptable, require less fuels, with reduced indoor air pollution, and require less time for cooking (GACC, 2014). The GACC has set a target to install 100 million improved cook stoves by the year 2020

(Bond and Templeton, 2011; Smith, 2010). This is expected to improve the health and financial status of households.

Recognising that clean and affordable energy is important to the achievement of the MDGs, and sustainable development, United Nations General Assembly (UNGA) recently declared the year 2012 as the International Year of Sustainable Energy for All (UNGA, 2011). The resolution 65/151 recognises the need to reduce the proportion of people using traditional biomass for cooking in developing countries. Further, recognising the fact that 1.3 billion people do not have access to electricity, and that 2.6 billion people use traditional biomass for cooking, UNGA further declared the period from 2014 to 2024 as the United Nations Decade of Sustainable Energy for All (UNGA, 2012). These resolutions are expected to bring renewed interest in sustainable energy and in particular lead to increased efforts to reduce traditional biomass use in developing countries.

Several developing countries have taken the initiatives to promote modern biomass and other improved technologies for cooking. The Chinese and the Indian biogas programmes are very good examples of efforts aimed at improving access to clean cooking energy in developing countries. As of the year 1988, there were about 4.7 million domestic biogas plants in China; however, due to a strong support from the Chinese government, the number increased considerably to about 26.5 million units by the year 2007 (Bond and Templeton, 2011). Similar efforts have resulted in installation of about 4 million biogas plants in India (Surendra et al., 2014). There are also efforts to promote the domestic biogas technology in the SSA. A notable example is the Netherlands Development Organisation (SNV) biogas programme, which is actively promoting biogas energy use in both Asia and SSA (Ghimire, 2013).

Several development countries have also made deliberate efforts to promote the use of improved biomass cook stoves, though the level of success remains low. Examples of notable success include the Chinese Cookstove (Smith et al., 1993) and the Kenya Ceramic Jiko stove programmes (Vahlne and Ahlgren, 2014).

1.4 Need for sustainability assessment of bioenergy systems

Due to sustainability challenges facing traditional biomass use, several developing countries are currently running programmes aimed at promoting improved bioenergy technologies for cooking. Efforts include introduction of technologies such as domestic biogas systems (Landi et al., 2013), gasification based on short rotation forestry

(Buchholz et al., 2012), and use of oil from plants such as Jatropha (*Jatropha curcas* L.) (Van Eijck and Romijn, 2008). These technologies offer several advantages over traditional biomass systems, including improved indoor air quality, higher fuel efficiency, and opportunities for employment in the supply chains. However, they are also faced by several challenges including high initial investment costs, potential competition with food production, impact on the environment and low levels of social acceptance (Buchholz and Volk, 2012; Phalan, 2009).

The multiplicity of challenges and benefits of bioenergy systems suggest the need to incorporate sustainability aspects during planning by holistically considering the social, economic, environmental and technological concerns. Sustainability assessment is a tool used guide policy and decision makers to select actions or policies that can enhance the sustainability of the society (Pope et al., 2004). It was derived from the concept of sustainable development, which is defined by the Brundtland Commission in 1987 as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission on Environment, 1987). Sustainability assessment is an important tool for decision making in order to justify choice of technologies for development and promotion. To aid analysis, sustainability has concept traditionally been divided into three pillars or dimensions, popularly known as the triple bottom line, which are; "people, planet and profit", also referred to as "people, planet and prosperity". This means that sustainability assessment is usually carried to ensure that projects lead to the desired socio-economic benefits to the target population while ensuring protection of the environment (Hacking and Guthrie, 2008).

1.5 Problem and rationale for the research

The background information given in this chapter suggests that access to clean and reliable energy for cooking is critical for the achievement of the MDGs and attainment of sustainable development. In addition, there is evidence of increasing commitments at global, regional and national levels to reduce adverse impacts of traditional biomass use in developing countries. Currently, there are a wide range of technologies that could play an important role in achieving the objective of improving access to modern biomass energy to households in these countries. Faaij (2006), gave a comprehensive review of possible conversion routes through which biomass can be used in a more sustainable manner.

However, the diversity of the technologies poses a serious challenge to decision makers in developing countries to objectively prioritise technologies to be promoted. Generally however, choice of technology should be determined by the principles of sustainability to ensure that they fulfil the energy needs of the current generation without compromising that of the future. The preferred choice should therefore ensure harmony with the social, economic, environmental and technological context of the target society.

Achieving the goal of attaining sustainability is however a very intricate problem, since the social, economic, environmental and technological objectives are often conflicting. This therefore calls for suitable decision making tools to guide policy and decision makers on the most suitable bioenergy technology to promote. The current challenge is that there are generally limited proven decision making aids to guide sustainable choice of biomass energy technologies in developing countries. Most of the existing tools were developed in industrialised countries and would require some tailoring to suit application in developing countries. Also, there is general lack of knowledge about the sustainability performance of the various modern biomass energy systems being promoted in developing countries. This therefore poses serious challenges to decision and policy makers on how to effectively select the most sustainable choice of modern biomass energy technology to promote.

1.5.1 Goal of the study

The overall goal of this study was to contribute to increased use of sustainable cooking energy in developing countries by improving the decision making process when selecting bioenergy technologies.

1.5.2 Specific objectives

The objectives of the study were to:

1. develop and implement a multi-criteria decision making methodology for assessing sustainability of bioenergy systems in developing countries;
2. develop and implement a tool for participatory appraisal of bioenergy systems;
3. evaluate the relative environmental performance of four bioenergy systems used in developing countries; and

4. investigate the configurations of biomass energy systems under study that could result in their improved sustainability.

1.5.3 Research questions

The study aimed at answering the following research questions:

1. What are the perceptions of Ugandan stakeholders about biogas, briquette, Jatropha charcoal cooking technologies, and how can it be assessed?
2. Can introduction of biogas, briquettes and Jatropha cooking technologies lead to improved environmental performance compared to use of charcoal?
3. Does use of biogas, Jatropha and briquette lead to overall sustainability of biomass cooking in developing countries, and how can the relative sustainability be measured?

1.5.4 The scope of the study

Uganda was purposely selected as the geographical locality for the study. This choice was made basing on the fact that Uganda is one of the developing countries with very low level of access to modern energy services. According to Buchholz and Da Silva, (2010), only 5% of Uganda population have access to electricity. Traditional biomass energy provides more than 90% of the primary energy needs of the country. The country has developed the Renewable Energy policy that encourages sustainable utilisation of modern biomass energy. Also, there is several development efforts aimed at promoting a variety of modern biomass energy use in the country. Examples include biogas, Jatropha plant oil, and briquetting. Detailed analysis of the bioenergy situation in Uganda is given in Chapter 2 of this thesis and in Okello et al., (2013b). The cooking energy technologies included in the study were the biogas, briquette gasification, Jatropha plant oil cooking and charcoal was taken as the reference system.

1.6 Outline of the thesis

This thesis is divided into two parts. Part I comprise of Chapter 1 to Chapter 3, and provide a general introduction to the study including study goals and objectives. It also gives detailed information on the status of bioenergy technologies and results of an assessment of energy potential of biomass residues in Uganda. Part II, begins from Chapter 4 to Chapter 9 of the thesis. Chapters 4 to 8 are dedicated to the development and implementation of sustainability assessment methods. Chapter 9 gives general summary to the study and highlights the main conclusions.

Part I: Introduction and state of the art analysis

This part of the thesis provides pertinent information that motivated the study. It is composed of three chapters. Chapter 1 gives the general introduction to the study, starting with a brief overview of the status of global energy supply. This is followed by an outlook of status of biomass energy use in developed and developing countries. Challenges of biomass sustainability in developing countries were discussed. Finally, the goal, objectives and scope of the study were articulated. The second chapter of the thesis provides overview of biomass energy technology in Uganda in particular. Detailed information about efforts made so far to promote improved bioenergy technologies and progress made by the government and other development partners is provided. The chapter also contains useful information on bioenergy stakeholders in Uganda. An evaluation of the bioenergy potential of biomass residues in Uganda was also carried out. Detailed description of the methods used and results of the study is given in Chapter 3 of the thesis. Results obtained in Chapter 2 and 3 were very important for formulating the conversion technology and choice biomass feedstock analysed in later chapters of the thesis.

Part II: Methodological development and application

The second part of the thesis provides results of the development and implementation of a sustainability framework of biomass energy systems. In Chapter 4, the concept of sustainability was introduced, followed by a succinct review of relevant literature on sustainability assessment methods. A justification of methods used in this study is given. This was followed by a presentation of sustainability assessment framework developed.

Sustainable development of bioenergy systems requires participation of stakeholders. An innovative method for participatory appraisal of bioenergy technologies in an environment with limited data was developed and implemented. Description of the method and results of an appraisal study of four bioenergy technologies in Uganda in provided in Chapter 5. The sustainability decision framework developed in Chapter 4 requires suitable set of criteria for its implementation. Twenty one criteria were selected to suit Ugandan environments by a panel of experts and multi-stakeholders and results given in Chapter 6. Chapter 7 provides an analysis of the environmental impacts of four energy systems under Ugandan conditions. The life cycle assessment method was used for the analysis. Results of the study were also used as evaluations of the environmental criteria for energy sustainability.

The aggregation of criteria to derive sustainability scores for the bioenergy technologies was carried out in Chapter 8. The chapter provides detailed description of the multi-criteria methodology used for sustainability assessment of four energy systems in Uganda. Different scenarios were analysed to evaluate possible feasible energy system orientations that results in better sustainability. Lastly, in Chapter 9, an overview of the results of the study is given followed by general discussions. Relevant conclusions were also highlighted and proposals for future research mentioned.

Chapter 2 – State of the art of bioenergy technologies in Uganda

Parts of this chapter was published in *Renewable and Sustainable Energy Reviews* as;

Okello, C., Pindozzi, S., Faugno, S., Boccia, L., 2013. Development of bioenergy technologies in Uganda: A review of progress. Renewable and Sustainable Energy Reviews. 18, 55-63.

Chapter 2 – State of the art of bioenergy technologies in Uganda

Summary

Biomass is a renewable energy resource; however, its exploitation raises concerns about its ability to sustain the growing demand and its negative impacts on the environment, particularly in developing countries. These concerns are more prominent on the African continent where high population growth rates is leading to high rates of deforestation due to expansion of agricultural land and increased demand for bioenergy. Use of traditional and inefficient bioenergy technologies and appliances also exacerbate the problem. This chapter presents a review of the efforts and progress made by different organisations in promoting improved bioenergy technologies in Uganda. The study was based on an extensive review of available literature on modern bioenergy technologies introduced in the country. It was found that there is high level of wastage of biomass resources since an estimated 72.7% of the population use traditional cooking stoves with efficiency estimated to be less than 10%. Inefficient cooking stoves are also blamed for indoor air pollution and respiratory illness reported amongst its users. Modern bioenergy technologies such as biomass gasification, cogeneration, biogas generation, biomass densification, and energy-efficient cooking stoves have been introduced in the country but have certainly not been widely disseminated. The country should pursue policies that will accelerate proliferation of more efficient bioenergy technologies in order to reduce the negative environmental impacts of bioenergy utilisation and to ensure sustainability of biomass supplies.

2.1. Introduction

Adequate supply of energy is crucial for the development of any nation. Currently, fossil fuels are the dominant global source of energy (Goldemberg and Teixeira Coelho, 2004). However, use of fossil fuels is associated with greenhouse gas emissions (GHG), which is blamed for global warming, and consequently, climate change. Therefore, emphasis is currently focussed on promoting use of renewable energy sources such as biomass, solar, wind and tidal energy. Biomass, in particular, is seen as a possible substitute to fossil fuels, and many developed countries are striving to increase the proportion of their primary energy supply from it (Faaij, 2006).

The situation in developing countries is however different because biomass has all along been the major source of energy (Akyüz and Balaban, 2011). In Africa for example, biomass accounts for about 30% of the energy consumption. Its use is more prominent in sub-Saharan Africa where it account for up to 80% of energy supply (Kebede et al., 2010). In Uganda, biomass contributes over 90% of energy requirements. However, despite the high contribution, the production and supply of biomass is still managed by the informal sector. Technologies employed from the production to consumption of biomass fuels are majorly traditional and inefficient and are associated with high levels of pollutants' emission. Extensive use of inefficient bioenergy technologies implies that biomass resources are being wasted; thus, contributing to increased rates of deforestation and related environmental concerns such undesirable change in biodiversity, degradation of soil and water resources. Improving the efficiency of bioenergy technologies could therefore, play a major role in conserving energy; hence, reducing the rate of environmental degradation.

In this perspective, the Government of Uganda, non-governmental organizations (NGOs), and several private agencies are currently promoting improved bioenergy technologies in the country. Examples of technologies promoted include improved (energy-saving) biomass cooking stoves, biogas, and biomass gasification technologies. Overtime, several independent reports of these programmes have been produced by the different actors in the sector. However, because they are made by different projects and individuals, it is very difficult to understand the overall impact of the bioenergy technology programmes in the country. Therefore, the aim of this study was to a conduct review of the progress made in the implementation of improved bioenergy technology programmes in Uganda. The objective is to present a succinct account of the level of proliferation of improved biomass technologies in the country.

2.1.1 Geographical, demographic and economic information

Uganda is a land locked country located in East Africa, between latitudes 01° 30′ S and 4° 00′ N; and longitudes 29° 30′ E and 35° 00′ E (Otim, 2005). It is bordered by Kenya in the east, Tanzania and Rwanda in the south, Democratic Republic of Congo in the west and South Sudan in the north. Figure 2.1 shows the location of Uganda on the African continent. The area of the country is approximately 241,550 km^2, out of which 41,743 km^2 is covered by open water bodies and swamps. The topography comprises plateaus in the central and northern parts of the country and mountains of Elgon and Rwenzori on the eastern and western borders, respectively. Overall, the elevation ranges from 620 m to 5110 m above mean sea level (UBOS, 2010a).

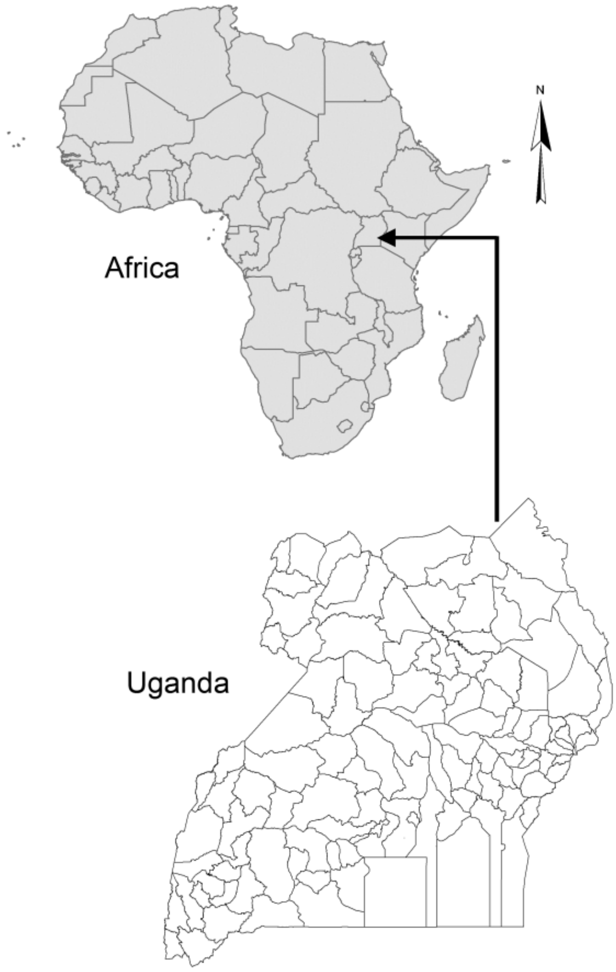

Figure 2.1. Map showing the location of Uganda on the African continent

According to UBOS (UBOS, 2002), by the year 2002, the country had a population of 24.4 million, characterized by an annual population growth rate of 3.4%. At the time, about 88% of the population lived in rural areas. Recent estimates by UBOS (UBOS, 2010a) indicate that the country‘s population by mid-year 2010 had grown to 31.8 million. A summary of the demographic and economic information on Uganda is given in Table 2.1.

2.1.2 Overview of the Ugandan energy sector

The per capita energy consumption of Uganda is estimated to be 1.63 GJ, which is very low compared to that of Kenya at 3.35 GJ and Italy at 123.89 GJ (2013). Energy supply in the country is predominated by biomass in form of firewood, charcoal and agricultural residues. Electricity and petroleum fuels are also used, but contributes is less than 10% of the total energy use. The contributions of the various forms of energy are illustrated in Figure 2.2.

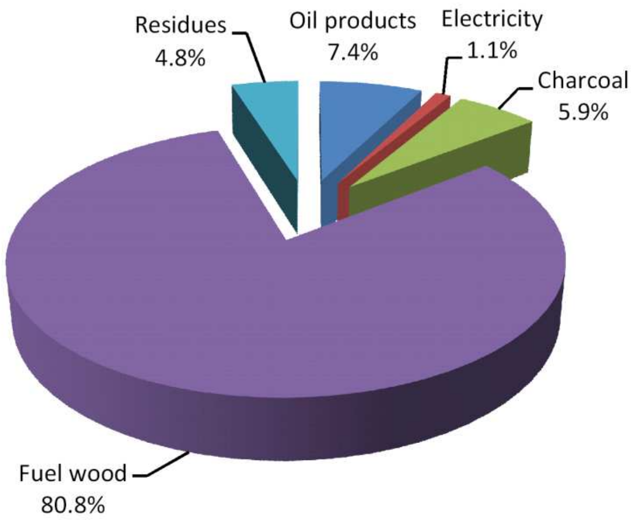

Figure 2.2. Energy use by category in Uganda

Electricity and petroleum fuels are considered as commercial energy in the country; however, biomass is not included in this category, probably because trade in biomass is predominantly informal, and in some cases illegal. In Uganda, biomass energy is used for cooking and heating in households, commercial and public institutions such as hotels, schools and hospitals. It is also used in small scale industries such as brick production and in various industries to supply process heat (Naughton-Treves et al., 2007).

Table 2.1. Demographic information and economic indices for Uganda

Parameter	Value	Year
Population mid-year (millions)	31.8	2010
Population density (persons per square km)	131.3	2008
Population growth rate (%)	3.3	2005 to 2010
Urban population (%)	12.8	2007
Gross domestic product (GDP)[a] (millions USD)[b]	15,829.00	2008
GDP per capita (USD)	500	2008
Forested area (%)	17.5	2007
Energy production, primary (x10^6 GJ)[c]	5.7	2008
Energy consumption per capita (GJ y^{-1})	1.6	2012
CO_2 emission estimates (x10^3 tonnes)	2704	2006
CO_2 emission per capita (tonnes)	0.1	2006

Sources: UBOS, (2010a) and United Nations, (2013)
[a]GDP - gross domestic product
[b]USD - United States Dollars

Table 2.2. Bioenergy consumption by sector in Uganda

Sector	Type of fuel (TOE[a] per year)		
	Wood	Charcoal	Residues
Residential	5,957,976	406,756	488,106
Commercial	1,242,267	195,855	0
Industrial	999,213	0	0
Total	8,199,456	602,611	488,106

Source: MEMD (2008)
[a] TOE – tonnes oil equivalent

Urban households predominantly use biomass in form of charcoal, while firewood and agricultural residues are principally used by rural dwellers. Table 2.2 shows the distribution of biomass consumption by sector (MEMD, 2008), from which it can be observed that the residential sector is the biggest consumer of biomass energy in the country. However, bioenergy technologies used in Uganda are mainly traditional and inefficient. Therefore, several organisations are currently promoting improved bioenergy technologies in the country. Table 2.3 gives a list of the organisations that are currently promoting improved bioenergy technologies in Uganda.

Table 2.3. List of organisations involved in improving bioenergy technology in Uganda

Name of Organisation	Type of organisation	Bioenergy technology promoted or used
Ministry of Energy and Mineral Development	Government agency	Policy formulation and regulations, and project implementation
Centre for Research in Energy and Energy Conservation	Makerere University; institution of higher learning	Research, development and dissemination of improved biomass technology
Appropriate Technology and Agricultural Engineering Research Centre	National Agricultural Research Organisation	Biogas technology
Nyabyeya Forestry College	Institution of higher learning	Training in biomass energy technology
Promotion of Renewable Energy and Energy Efficiency Programme	German Agency for International Cooperation	Improved biomass stoves
SNV Uganda	Netherlands Development Organisation	Biogas technology
Joint Energy and Environment Project	Non-Governmental Organization (NGO)	Biogas technology, improved biomass stoves
Heifer International	NGO	Biogas technology
United Nations Development Programme	United Nations agency	Multifunctional platform based on biodiesel

Table 2.3. Continued …

Norwegian Refugee Council	NGO	Improved biomass stoves
Agency for Cooperation and Research in Development	NGO	Improved biomass stoves
CARITAS International	NGO	Improved biomass stoves
African Medical Research Foundation	NGO	Biogas technology
SEND A COW Uganda	NGO	Biogas technology
Africa 2000 Network Uganda	NGO	Biogas technology
KULIKA Community Development and Education in Uganda	NGO	Biogas technology
Sustainable Sanitation Water Renewal Systems	NGO	Biogas technology
East African Energy Technology Development Network	NGO	Bioenergy technology promotion, capacity building, networking
Pamoja Inc.	NGO	Gasifier stoves for domestic applications
Kakira Sugar Works (1985) Limited	Sugar manufacturing company	Combined heat and power generation
Kinyara Sugar Works Limited	Sugar manufacturing company	Combined heat and power generation
Sugar Corporation of Uganda Limited	Sugar manufacturing company	Combined heat and power generation, ethanol production
Uganda Stove Manufacturer's Limited	Private company	Production of improved biomass stoves
Nexus Bio-diesel Limited	Private company	Biodiesel production from jatropha
Royal Zan Zanten	Private flower growing firm	Biodiesel from jatropha
Muzizi Tea Estate	Private tea producing company	Gasification for electricity generation
Paramount Cheese Dairies Limited	Private company	Gasification for industrial heat production
Green Heat (U) Limited	Private company	Biogas and briquetting technologies
Kampala Jillotine Suppliers Limited	Private company	Biomass briquetting

Petroleum fuels contribute about 7.4% of primary energy consumption in Uganda. The major forms of petroleum products used are: gasoline, diesel fuel, kerosene, fuel oil, aviation fuel and liquefied petroleum gas (LPG). Diesel fuel takes the biggest share of petroleum consumption and is mainly used to power heavy vehicles, and for electricity generation. Gasoline is used for powering light vehicles and small engines. Kerosene is mainly used by the rural households for lighting. Most petroleum products are imported into the country and their prices usually fluctuate with international rates. Recent development in the petroleum sector includes a discovery of an estimated 2.5 billion barrels of petroleum reserves in the western part of the country (Veit et al., 2011). In the short term, the government plans to build a mini-refinery of 6,000 to 10,000 barrels per day to supply the country's growing petroleum fuel needs (GTZ, 2009).

Electricity, mainly from hydropower generation stations is also used in the country. However, the level of access to electricity in Uganda is estimated to be only 5%, making it one of the lowest in Africa. In rural areas where about 84% of the population leave, access to electricity is less than 2% (Buchholz and Da Silva, 2010; Kaijuka, 2007). Even in urban areas, with higher accessibility rates, majority of households still heavily rely on charcoal to meet their daily energy needs. The low level of access could be explained by the low generation capacity and the high capital and operating costs for developing the electricity sector, especially for less developed economies like Uganda (Kaijuka, 2007). Currently, the installed capacity of main hydroelectric power complex located in Jinja is 380 MW. However, the effective generation capacity dropped considerably to about 100 MW in 2005, before rising eventually to about 140 MW in the year 2010 (Muhoro, 2010). The drop in generation capacity was attributed to the drastic fall in Lake Victoria water levels as a result of prolonged drought in the East African region (UBOS, 2010a). As a result, the country faced a major electricity crisis since the year 2005. In order to overcome the shortfall, the government contracted independent power producers, which by the year 2010, were supplying about 150 MW of electricity mainly from diesel powered generation plants to the national grid (UBOS, 2010a).

Meanwhile, to meet the shortfall, construction of a 250 MW Bujagali hydroelectric power station is currently on-going. Biomass, mainly bagasse from sugarcane processing, is also used in Uganda to produce about 22 MW of electricity through cogeneration (GTZ, 2009). Several stand-alone diesel and gasoline powered generators are also installed in the country by individual consumers. However, their contribution to the total electrical power consumption is not known.

Nevertheless, Uganda has high potential to produce hydroelectricity. It is estimated that the hydroelectric power potential along the river Nile alone is about 2000 MW. Additional potential of about 200 MW is available from several other smaller waterfalls distributed all over the country (Muhoro, 2010). Uganda is also rich in other energy sources such as solar and geothermal resources. Currently, there is effort to promote solar photovoltaic (PV) and thermal systems but their contributions still remain insignificant to the country’s energy supply.

2.2 Bioenergy conversion technologies

There are several routes through which biomass can be converted into different forms of liquid, solid or gaseous fuels. These processes are classified broadly as thermo-chemical, biochemical and mechanical extraction (McKendry, 2002a; Panwar et al., 2012). A detailed illustration of the processes is shown in Figure 2.3. In this study, we examined the level of penetration of each of these conversion routes in Uganda. In addition, we also discussed the combined heat and power generation (CHP) and biomass densification technologies. A brief explanation of the principles behind these processes is introduced in each section followed by a detailed review of the level of penetration of each technology in Uganda.

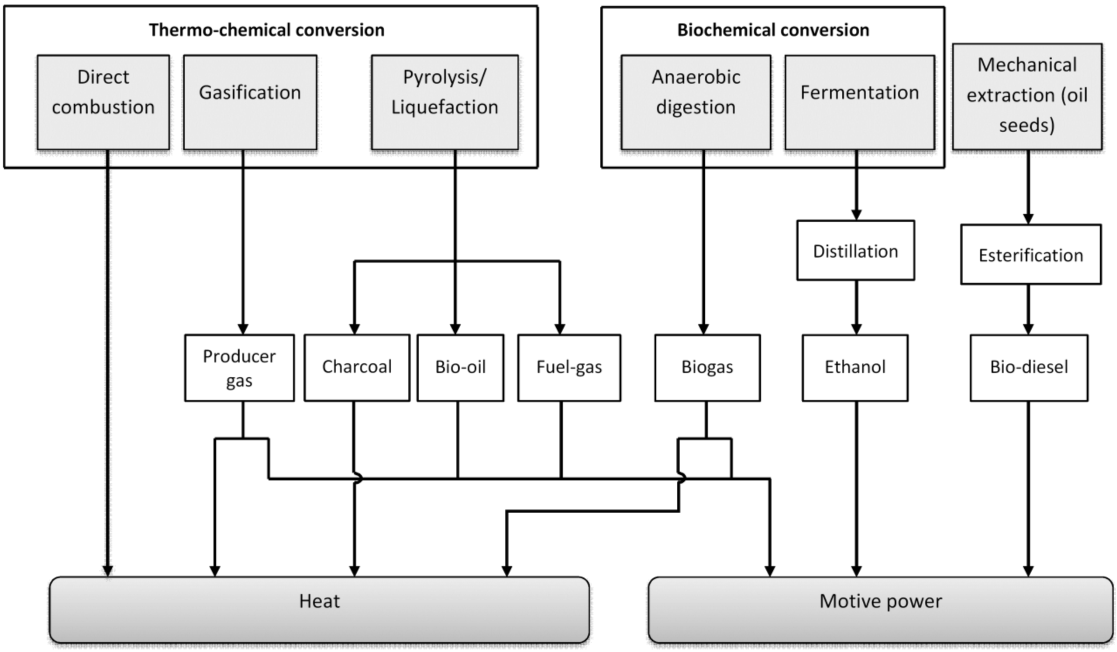

Figure 2.3. Bioenergy conversion technologies. Modified from Faaij, (2006), McKendry, (2002a) and Panwar et al., (2012).

2.2.1 Traditional biomass combustion technologies

It is estimated that about three billion people worldwide use solid fuels such as coal, wood and animal dung to meet their domestic energy needs (WHO, 2006). Such fuels are mainly used in developing countries, where an estimated 2.2 billion people burn them in traditional cooking stoves. Use of traditional stoves is more prominent in sub-Saharan

Africa, where it is estimated that 94% of the population use them for cooking and heating (Legros, 2009). For the case of Uganda, it is estimated that about 87.5% of households use traditional stoves for domestic energy conversion applications. The three-stone stoves and the traditional charcoal stoves are used by 72.7% and 14.8% of households, respectively (Byakola and Mukheibir, 2009). In three-stone stoves, firewood is burnt between three stones that act as the hearth as well as support to the cooking vessel. Firewood is pushed into the hearth through the open spaces between the stones as it burns (Jetter and Kariher, 2009). Traditional charcoal stoves, on the other hand, are locally made using scrap metal materials such as roofing sheets and oil drums, but do not have insulation lining; therefore, leading to excessive heat loss during operation. The efficiency of these stoves is reported to be less than 10% (Cuvilas et al., 2010; Faaij, 2006).

The tradition stove technologies, are also known to be a source of indoor air pollutants such as particulate matter and carbon monoxide (Adkins et al., 2010). Exposure to indoor air pollutants emitted by these stoves causes eye irritation and respiratory related diseases that mainly affect women and children in developing countries (WHO, 2006). According to World Health Organisation (WHO), about 1.5 million people die annually due to illnesses caused by exposure to indoor air pollutants emitted by inefficient cooking stoves (WHO, 2006). In sub-Saharan Africa, the mortality burden is estimated at 400,000 people annually (Kebede et al., 2010; WHO, 2014). Another problem associated with combustion of biomass in traditional stoves is its contribution to global warming resulting from products of incomplete combustion (Legros, 2009).

2.2.2 Improved biomass combustion technologies

Improved biomass stoves are built to have higher efficiencies compared to the traditional counterpart. They have been in use for at least 100 years, but recent emphasis to their use arose due to the petroleum crisis of the 1970s. Increased petroleum prices coupled with anticipated fuel wood exhaustion led to renewed emphasis on promoting improved biomass cooking stoves (Barnes et al., 1994). Recently, environmental concerns, together with the need for improved health of rural households have given more legitimacy to the promotion of improved biomass stoves (García-Frapolli et al., 2010). Improved biomass stoves have several advantages over their traditional counterpart including increased fuel savings, reduced cooking time and costs for the health sector, increased forest conservation, and reduced emissions of air pollutants (Kees and Feldmann, 2011). There are several designs of improved biomass stoves available on Ugandan market, examples can be found in Jetter et al., (2009). The principle considerations in the design of improved stoves include reducing heat loss by insulating the walls of the combustion chamber and controlling air flows during combustion. Figure 2.4 illustrates a comparison between traditional charcoal stoves (Fig. 4a) and improved ones (Fig. 4b), both of which are commonly used in Uganda. The principal difference in this case is that the walls of improved stoves are insulated while that of the traditional one is not.

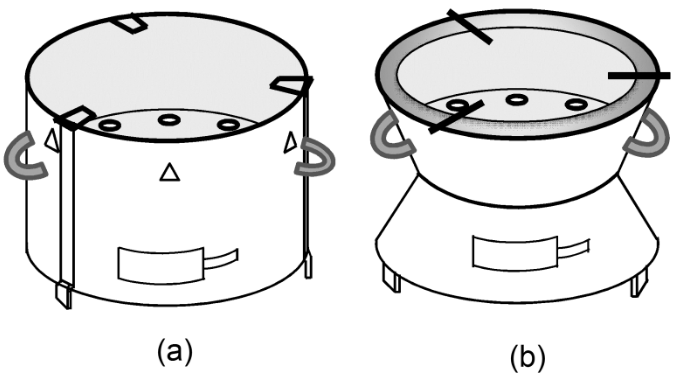

Figure 2.4. Charcoal stoves. (a): traditional charcoal stove, (b): improved charcoal stove

The Government of Uganda underscores the importance of improved biomass stoves and has a set target of installing 4 million improved wood fuel stoves and 250,000 improved charcoal stoves by the year 2017 (Panwar et al., 2012). Energy-saving stoves, based on the rocket stove principle are being promoted by the government with support of German Agency for International Cooperation under the "promotion of renewable energy and energy efficiency programme". Under this programme, at least 500,000 energy-saving biomass stoves have so far been installed since the year 2005 (Kees and Feldmann, 2011). Makerere University is currently spearheading research and development of energy saving stoves in the country and several NGOs are involved in dissemination programmes through training of artisans in stove production.

The role of the private sector in the dissemination of improved biomass stoves in Uganda is also becoming important. An example of a private sector involvement is the "UGASTOVE" project that specialises in producing improved charcoal stoves for use in the domestic and commercial sectors such as restaurants, schools and hospitals. A detailed illustration of the design of UGASTOVE biomass cooking stoves is given by Adkins et al., (Adkins et al., 2010). The UGASTOVE company also produces improved wood stoves for rural households and institutions. It was estimated that over a seven-year period, the company would sell 180,000 improved stove units resulting in a potential of saving approximately 600,000 tonnes of carbon dioxide equivalent (Simon et al., 2012).

However, despite these efforts, the current level of adoption of improved biomass combustion technology is still low in the country. According to Byakola and Mukheibir (2009), only 8.7% of Ugandan households use improved biomass stoves.

2.2.3 Biomass pyrolysis

Pyrolysis is the thermo-chemical conversion of biomass under limited supply of oxygen at temperatures ranging from 350°C to 700°C, (Goyal et al., 2008). Products of pyrolysis include charcoal, bio-oil or fuel gas, the proportion of which varies depending on the temperature and residence time of the biomass material in the reactor (Panwar et al., 2012). Explanations of the effects of temperature and residence time on the pyrolysis process and products are available in literature (Goyal et al., 2008; McKendry, 2002a; Panwar et al., 2012). The most common pyrolysis method is carbonisation, which is a slow pyrolysis of biomass at temperatures of about 400°C (Panwar et al., 2012). Carbonisation is widely used in developing countries for the production of charcoal (Adam, 2009). There are several technologies available for carbonisation including traditional methods such as earth pit, and earth-mound kilns. Examples of improved technologies include brick and metal kilns (Booth, 1983).

Charcoal making is a major source of employment and income in Uganda and is mainly carried out by numerous small, economically weak and unorganised individuals (Sankhayan and Hofstad, 2000). However, these are not necessarily the poorest clusters of their communities (Khundi et al., 2011). The traditional earth-mound kiln (Adam, 2009) is the dominant type of carbonisation technologies in Uganda. It involves stacking wood lots in mounds of about 1.5 m high, followed by sealing with earth to limit air during carbonisation. An opening is provided for ignition of the wood, after which it is sealed off with soil. However, the sealing is not uniform and it is common for air to escape into the kilns leading to complete combustion of the biomass. Consequently, the efficiency of this method is very low, estimated to be between 10 to 15 % (Knöpfle, 2004). Significant loss of the product also occurs at the production site due to the difficulty in recovering the charcoal that has been mixed with soil during the carbonisation stage. The packaging technology used also contributed to material loss through crushing into powder during transportation. Opportunities therefore exist for reducing charcoal losses both during production and transportation stages.

2.2.4 Biomass gasification

Gasification is the partial oxidation of carbonaceous feedstock such as coal and biomass materials, at elevated temperature, into a gaseous energy carrier (Bridgwater, 1995). Gasification takes place when biomass is heated in a gasification medium such as air, oxygen or steam (McKendry, 2002b). The product of biomass gasification is a mixture of several gases, collectively called producer gas, or synthesis gas. Constituents of the producer gas include carbon dioxide, carbon monoxide, hydrogen, methane, steam, together with traces of higher hydrocarbons. Others are inert gases that result from the gasification agent, and contaminants such as tars, char particles, ash and oils (Belgiorno et al., 2003). Gasification process takes place in a reactor called gasifier, which vary greatly in design, but are broadly classified as fixed bed, fluid bed and moving bed. Other design configurations are; rotary kilns, cyclonic and vertex reactors (Knöpfle, 2004). In general, fixed-bed gasifiers are known to be the most suitable for gasification of solid biomass. Producer gas can be used as fuel in internal combustion engines, burned to produce heat, or used in the synthesis of liquid transportation fuels, hydrogen and other chemicals (Balat et al., 2009).

Gasification technology is not widely used in Uganda; nevertheless, a case of interest is reported at Muzizi tea estate, located in the western part of the country (Buchholz and Volk, 2007; Mangoyana and Smith, 2011; von Maltitz and Staffor, 2011). The company installed a GAS 250® system manufactured by Ankur Scientific in India. Biomass for the gasifier is from 99 ha of Eucalyptus (*Eucalyptus grandis*) plantation, part of which is used in a boiler to generate steam for drying black tea (*Camellia sinensis*). Though rated at 200 kW electrical power, the average power output was reported to be only 87 kW (Buchholz and Volk, 2007). Available literature did not give an explanation for the low output reported. Nonetheless, the unit cost of electricity from the gasifier was estimated to be 0.03 United States Dollars (USD) per kilowatt hour and was much lower than that of diesel generated electricity, which was approximately 0.3 USD kWh^{-1}. The system was estimated to replace 120,000 litres of diesel per year, or an equivalent of 314 tonnes of carbon dioxide emission. The challenge of the system was that its capital cost of 2087 USD kW^{-1} was very high, especially for developing countries like Uganda. Economic analysis showed that the gasifier plant was only marginally viable with a payback period of about 9.5 years (Mangoyana and Smith, 2011).

2.2.5 Biogas generation technology

Biogas is a mixture of gases produced during anaerobic decomposition of organic matter and is mainly composed of methane and carbon dioxide and trace gases such as hydrogen sulphide, ammonia, water vapour and volatile organic compounds (Tsai, 2007). Slurry, the by-products of the digestion process is a bio-fertilizer and soil conditioner, which can be used to improve crop yields (Walekhwa et al., 2009). The main advantage of biogas technology is that it utilises wastes from the agricultural, industrial or municipal sectors and therefore, its use does not exhaust crop production resources. Other benefits include contributions in slowing down deforestation rates, and reducing over dependence on fossil fuels (Parawira, 2009). The technology also reduces drudgery associated with firewood collection and leads to time savings that could be used for other economic ventures (Mwakaje, 2008). Combustion of biogas produces less pollutants; therefore, its use leads to improved indoor air quality resulting in improved health of women and children, who are the most exposed group to the risk (Srinivasan, 2008). Use of biogas for energy purposes is also an effective means of limiting methane flows to the atmosphere from decaying organic matter, thus contributing to reduction in greenhouse gas emission.

Biogas technology was introduced in Uganda in the 1950s by the Church Missionary Society. Currently, the technology is being promoted by government agencies such as National Agricultural Research Organization (NARO) and the Ministry of Energy and Mineral Development. Non-governmental organizations such as Heifer International Project, Adventist Development and Relief Agency, amongst others are also promoting the technology. The most commonly used type of bio-digester is the fixed-dome design that was modified from the Chinese design by the Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC) in Tanzania (Sasse et al., 1991). The CAMARTEC bio-digester design that is usually constructed below ground surface is illustrated in Figure 2.5.

Volumes of these digesters range from 8 m^3 to 16 m^3. The floating-dome and the tubular bio-digester designs were introduced in the country but not commonly used (Walekhwa et al., 2009). The fixed-dome digester is preferred because it is more durable than the tubular design and cheaper to install than the floating dome counterpart. Costs of floating dome digesters are higher because of the high costs of steel used in the fabrication of gas chamber. Designs of the floating dome and tubular digesters introduced in Uganda are similar to those illustrated by Nzila et al., (2012).

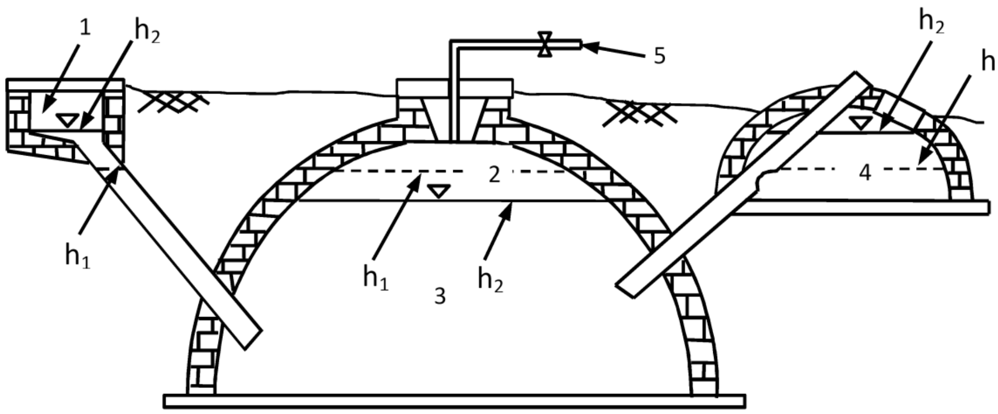

Figure 2.5. The CAMARTEC biogas digester. 1: mixing tank, 2: gasholder, 3: digester, 4: compensation tank. h_1 : level of slurry before gas production, h_2 : level of slurry when with gas is in the holder. Source: Parawira, (2009)

The main material used for biogas generation in Uganda is cow dung and it is estimated that the dung generated could support installation of over 250,000 family-sized digesters. The government has a target of installing 100,000 family-sized digesters by the year 2017 (MEMD, 2007). Overall, it is estimated that about 500 biogas digesters have so far been installed, however, less than 50 % are operational (Walekhwa et al., 2009). A good case study of bio-digester installed in the country is one with a 50 m^3 capacity per day at Waga Waga School (Mangoyana and Smith, 2011). The low level of adoption of biogas technology has been attributed to limited technical skill, for installation, operation and maintenance and high capital costs (Kariko-Buhwezil et al., 2011; Sengendo et al., 2010).

2.2.6 Fermentation

Bioenergy conversion through fermentation involves production of ethanol from sugar or starch-rich biomass, and is the most widely used biofuel production method in the world (Faaij, 2006). The ethanol is purified through an energy-intensive distillation process (McKendry, 2002a). The technology is widely used in Brazil, the United States and Europe for the production of fuel ethanol.

In Uganda, molasses from sugarcane processing has been identified as a possible raw material for production of ethanol with an estimated potential of 119 x 10^6 litres per year (Jumbe et al., 2009). Sugar Cooperation of Uganda Limited, a mill sugar production company, has the only ethanol production plant in Uganda with annual production of 1.5 million litres (Batumbya Nalukowe, 2006). The company is expanding is production capacity to 9 million litres. The ethanol produced is used as an industrial chemical, and not used widely as a bioenergy source. However, lack of appropriate policy to guide the development of this sector is reported to be a possible barrier to the development of bio-fuel in the country (NEMA, 2010).

2.2.7 Mechanical extraction

Mechanical extraction is the separation oils from seeds of plants with high oil contents under pressure. Examples of seeds from which oils can be extracted include rapeseed, sunflower, soya bean (Demirbaş, 2001). The oils can then be converted into esters through a process called esterification. The esters, also called biodiesel, can be used to substitute diesel in engines (Faaij, 2006). The challenge with the technology is currently the high cost of the esters compared to fossil fuels.

The use of biodiesel for motive power generation was initiated in Uganda through a pilot project supported by the United Nations Development Programme (UNDP) in 2007 (Karlsson and Banda, 2009). The project was initiated on the basis of multifunctional platforms (MFP) that was successfully implemented in Mali (Brew-Hammond, 2010; Denton, 2004; Nygaard, 2010). Two MFPs, powered by oil extracted from Jatropha seeds, were installed in Masindi district (Karlsson and Banda, 2009). The engine provided motive power source to equipment such as grinding mills, oil presses and generators. There are also small scale biodiesel production activities in Mukono district, where a flower firm and local farmers are using Jatropha oil for biodiesel production (Kyamuhangire, 2008; Pillay and Da Silva, 2009). Another pilot project was also initiated through collaboration between GTZ and ministry of energy in Luwero district (Kyamuhangire, 2008). Nevertheless, biodiesel is a relatively new bioenergy conversion technology in Uganda and most trials are still on pilot scales.

2.2.8 Cogeneration

Cogeneration, also known as combined heat and power (CHP) generation, is the simultaneous production of mechanical or electrical and thermal energy from a single energy carrier such as oil, coal, natural or liquefied gas, biomass or solar (Biezma and Cristóbal, 2006; Onovwiona and Ugursal, 2006). The advantage of cogeneration is that it is more energy efficient compared to when mechanical, thermal or electrical energy is produced independently (Mbohwa and Fukuda, 2003).

Biomass materials which provide opportunity for cogeneration in Uganda include bagasse; a by-product of mill sugar processing, coffee and rice husks, and wood wastes such as wood shavings, saw dust and off-cuts. Bagasse in particular provides an excellent opportunity for CHP because they are produced in large quantities, mainly in three sugar factories: Kakira Sugar Works, Kinyara Sugar Works and Sugar Corporation of Uganda Limited. The three factories process a combined average of 130,000 tonnes of mill sugar annually (UNDP and UNEP, 2009). According to UNDP and UNEP (UNDP and UNEP, 2009), the bagasse generated from the factories has potential to generate 46 MW of electricity, in addition to process heat. Currently, the combined electricity generation from bagasse from the three factories totals 22 MW out of which 12 MW is supplied to the national grid and the rest is used internally for sugar processing (Kaijuka, 2007). However, the installed CHP capacity cannot consume all the bagasse generated during sugar processing; consequently, it is common practice to burn the excess bagasse in open fire (Bingh, 2004).

2.2.9 Biomass densification

Biomass densification is the conversion of loose biomass into high density solid material through application of pressure (Okello et al., 2011). Normally, biomass materials such as agricultural and forest residues have high moisture content, irregular shapes and sizes, and low bulk density, making it very difficult to handle, transport, store and utilize. Combustion of loose biomass is associated with low thermal efficiency, high particulate matter emissions (Chen et al., 2009). Biomass densification provides the solution to these problems by increasing the initial bulk density of the loose biomass making it easier and cheaper to handle, transport, and store. Densified biomass, are also easily adopted for direct combustion, gasification and pyrolysis or co-firing with coal (Kaliyan and Vance Morey, 2009). Products of biomass densification have well defined shape and size and are broadly classified as pellets, briquettes and cubes with bulk density ranging from 450 to 700 kg m^{-3} (Kaliyan and Morey, 2010). There are a number of technologies that have been developed for biomass densification including; the piston press, screw press, hydraulic press and the roller press (Chen et al., 2009).

Biomass densification could play an important role in improving the utility of the large quantity of loose biomass materials generated in Uganda. Biomass densification is currently being employed in Uganda but the level of adoption of the technology still remains very low. Briquetting technology has in particular been taken up by poor urban communities of Kampala as an adoption strategy to increasing cost of energy in the country, and as a measure for solid waste management. The technology used by the community is very crude. It involves mixing banana peelings with charcoal dust and anthill soil to make briquettes (Kareem and Lwasa, 2011; Lwasa, 2010). At industrial scale, briquetting is being used by a private company; Kampala Jellitone Suppliers, which produces 2000 tonnes of briquettes annually. The company uses biomass residues such as rice husks, coffee pulp, maize stalks and sawdust to make biomass briquettes, which is sold to various institutions such as hospitals, schools and universities as fuel for cooking (Ashden Awards, 2009). Apart from these examples, there are several informal small scale producers of briquettes.

2.3. Discussions

The present review has shown that biomass remains the predominant source of energy in Uganda. The level of adoption of improved bioenergy technologies in the country is still very low. It is predicted that the in the near future, the country‘s demand for biomass energy will increase in line with population growth. High rate of urbanisation in the country is likely to result in increased demand for charcoal fuel. Dissemination of improved bioenergy technology could play an important role in ensuring sustainability of biomass supply through efficiency improvement. However, despite the concerted efforts by various players in the bioenergy sector, use of modern and efficient bioenergy technologies in the country remains intangible.

The level of dissemination of improved bioenergy technology in Uganda is similar to that of other sub-Saharan Africa countries, where majority of the population still rely on inefficient traditional cooking stove technologies. However, some countries on the African continent have had very successful programs in the bioenergy technology development. An example is Mauritius where co-generation of bagasse meets over 25% of the country’s electricity supply. Other countries that registered significant success in bioenergy programmes include Kenya, Malawi and Zimbabwe. The bioenergy programmes in these countries aimed at producing ethanol for blending with petroleum for use in vehicles (Karekezi, 2002). However, the overall picture is that promotion of modern bioenergy technologies is very low on the African continent. This could probably be explained by the inadequate support to modern bioenergy technology in Africa as explained by Amigun et al., (2008).

Elsewhere, it can be observed that countries that have had strong institutional support to bioenergy programmes have registered significant success in promoting improved bioenergy technologies. A good example is India, which registered significant success in modern bioenergy development through government programmes implemented by the Ministry of New and Renewable Energy. Between 1984 and 2003, an estimate of 35 million improved cooking stoves had been disseminated. The biogas programme of India also had over 3.8 million bio-digesters installed. The success was attributed to investment in research and technology development and dissemination through policy measures and incentives (Ravindranath and Balachandra, 2009). Brazil is another example of a country with very successful bioenergy programme based on ethanol produced for molasses. Currently, over 80 % of vehicles in Brazil operate on a blend of ethanol and petroleum resulting in over 20 % substitution of petroleum use in the vehicle industry (Hira and De Oliveira, 2009). The Brazilian success is attributed to state intervention in the establishment and support to the ethanol programme, infrastructural development as well as research and development (Hira and De Oliveira, 2009). In the European Union (EU), development of bioenergy technologies is being promoted by various EU policies aimed at increasing the use of renewable energy sources. Under the current EU directive, member states have targets for renewable energy use so that the overall EU renewable energy share is at least 20 % of the total primary energy consumption by the year 2020 (European Commission, 2009). The EU policies is expected to almost double electricity generation from biomass from about 22.5 GW in 2010 to 43 GW in 2020 (Jäger-Waldau et al., 2011).

In all examples of successful bioenergy development projects above, it is pointed out that favourable policies and incentives, research and development played an important role in the development of the technologies. However, there are several barriers that seem to hinder the development of bioenergy technologies. For example, Painuly (2001) identified barriers to renewable energy penetration which include market failure and distortions, economic and financial constraints, institutional and technical barriers, social and cultural behaviour, lack of infrastructures, government policies, and environmental barriers. Barry et al., (2011), identified up to 13 factors that may influence the choice of renewable energy in Africa. Also, Walekhwa et al., (2009) found that socio-economic and demographic characteristics of households play important roles in the adoption of biogas technology in Uganda. However, it is generally not very clear which of these factors have predominant roles in Uganda. One question that remains to be answered is whether Ugandan policy framework is favourable for promoting the development of bioenergy technology.

2.4. Conclusions

From this study, it can be concluded that the rate of adoption of improved bioenergy technology remains very low in Uganda. The reasons for the slow technological adoption and diffusion have been attributed to high capital costs, and lack of technical expertise, amongst others. However, more effort is still required in developing clear understanding of the reasons for the low levels of dissemination of improved bioenergy technologies, and to developing suitable policy frameworks for bioenergy technology development.

Chapter 3 – Bioenergy potential of agricultural and forest residues in Uganda

Parts of this chapter was published in *Biomass and Bioenergy* as;

Okello, C., Pindozzi, S., Faugno, S., Boccia, L., 2013. Bioenergy potential of agricultural and forest residues in Uganda. Biomass and Bioenergy. 56, 515-525.

Chapter 3 – Bioenergy potential of agricultural and forest residues in Uganda

Summary

Biomass is the major source of energy in most developing countries. However, there are concerns about the sustainability of biomass supplies and the environmental impacts resulting from their use. Use of residues could contribute to ensuring sustainable supply of biomass energy. This study presents findings of an evaluation of the energy potential of agricultural and forest residues in Uganda using census data of the year 2008/2009. Annual productions of crop and forest residues were estimated using residue-to-product ratio (RPR) method. Energy potential of each residue class was then determined basing on their respective lower heating values. The biogas generation potential of each animal category was used to evaluate the energy potential of animal manure. Results showed that the total energy potential of the residues amount to about 260 PJ y^{-1}, which is about 70% of gross biomass energy requirement of Uganda for the year 2008. Crop residues had the highest contribution of about 150 PJ y^{-1}, followed by animal residues with a potential of 65 PJ y^{-1}. Maize residue is the predominant crop residue with energy potential of 65 PJ y^{-1} followed by beans and banana, each at 16 PJ y^{-1}. This study indicates that agricultural and forest residues can be a major renewable energy source for Uganda. When sustainably utilised, biomass residues could contribute to reduction in environmental degradation in the country.

3.1 Introduction

Biomass is the major source of energy contributing over 90% of the energy requirements of Uganda (MEMD, 2008; Okello et al., 2013b). However, of recent, rapid population growth, urbanisation and industrialisation have increased the demand for biomass resources in the country. Annual demand for woody biomass and charcoal is reported to be increasing at about 3% and 6%, respectively (Kanabahita, 2001). The main source of biomass energy in the country is from wood harvested from unmanaged natural forests. Natural forests in Uganda are dominated by slow-growing species, thus high rates of harvesting may lead to deforestation and environmental degradation. A report on the global forest resource assessment of 2005 (FAO, 2006), indicates that between the year 2000 and 2005, the annual deforestation rate in Uganda was 2.2%, and is one of the highest in the world. Moreover, the demand for biomass energy is expected to increase with increasing population in most sub-Saharan African countries (Karekezi and Kithyoma, 2002; Kebede et al., 2010). One would therefore expect a similar trend in Uganda, where population growth rate is about 3.3% per year (Okello et al., 2013b). This leads to concerns about the sustainability of forest biomass to supply the increasing demand in the country (Kayanja and Byarugaba, 2001; Naughton-Treves et al., 2007).

It is therefore important to source for alternative energy sources to meet the increasing demand for biomass energy. Several options are available, but among the most promising is the use of biomass residues. The potential of biomass residues to meet energy needs has attracted interest of several researchers in the recent past. For example, Fernandes and Costa (Fernandes and Costa, 2010) evaluated the potential of agricultural and forest residues in Marvão province of Spain and found an annual potential of 160 TJ. Also, Vasco and Costa (Vasco and Costa, 2009), evaluated the energy potential of forest residues in Maputo province of Mozambique, and reported that residues could substitute about 32% of the 2004 energy requirements of the province. Other examples of studies on energy potential of biomass residue were carried out at national levels in Zimbabwe (Shonhiwa, 2013) and Romania (Scarlat et al., 2011). Other studies have also been conducted at a global scale; for example, Gregg and Smith (Gregg and Smith, 2010) evaluated the global and regional potential of agricultural and forestry residues, and reported a global potential of 50 EJ y^{-1}. The main advantage of national level studies is their ability to provide more detailed information required for decision making at local levels.

This study therefore aims at evaluation the energy potential of agricultural and forest residues in Uganda. Being a predominantly agricultural-based economy, large quantities of biomass residues from the crop and animal production sectors are generated throughout the country. It is a common practice to burn the residues in cultivated areas as a means of agricultural land preparation. Residues generated from agricultural processing facilities are burdensome to processors because of costs incurred in their disposal. Forest residues are also generated during logging and wood processing operations. However, their use as an energy source is still very limited in the country. Use of biomass residues for energy is of advantage since it does not require major changes to the current combustion technologies in the country. Also, when well-managed, use of residues is not competitive with land and water resources required for food production. It also results in reduced deforestation and environmental degradation.

One of the most important steps in developing biomass energy supply from residue is to evaluate their spatial and temporal availability. Such an analysis would provide useful information for decision makers on the opportunities for using biomass residues for energy application in different parts of the country. However, the temporal and spatial distribution of the energy potential of biomass residues in Uganda is currently not known. The present study was therefore conducted with the objective of evaluating the energy potential of agricultural and forestry residues in Uganda.

3.2 Materials and methods

3.2.1 Estimating potential of crop residues

To estimate the energy potential of crop residues, the procedure documented by Sigh et al., (Singh et al., 2008) was used with some minor modifications. The energy potential of agricultural residues was calculated using Equation 3.1;

$$Q_{AR} = \sum_{i=1}^{n} \left(C_i \times RPR_i \times LHV_i \right) \quad (3.1)$$

where, Q_{AR} is the annual gross energy potential of agricultural residues at 100% efficiency, C_i is the annual production of crop i. Factor, n is the total number of residue categories. The variable RPR_i is the residue-to-product ratio of crop i, and LHV_i is the lower heating value of a given crop residue. Parameters such as moisture content, lower heating values and residue to product ratio were obtained from available literature (Amoo-Gottfried and Hall, 1999; Bhattacharya et al., 2005; Duku et al., 2011; Koopmans and Koppejan, 1997; Perera et al., 2005). Other literature from which data were obtained are (Clarke et al., 2008; Jingura and Matengaifa, 2008; Junfeng et al., 2005; Qingyu et al., 1999; Tock et al., 2010)

3.2.2 Animal manure

To estimate the energy potential of animal residues, manure generated by cattle, sheep, goats, pigs, poultry and humans were considered. Properties of animal manures necessary for estimating their energy potential include daily volatile solid production per animal and biogas yield per kilogramme of volatile solid. These parameters were obtained from literature (Bhattacharya et al., 1997; Sajjakulnukit et al., 2005) and used to estimate the amount of biogas that can be produced by each livestock category. The energy potential of biogas was assumed to be 20 MJ m^{-3} as recommended by Perera et al, (2005).

3.2.3 Determining the potential of forest residues

Forests residues are of two types, namely; the logging residues and wood processing residues. Logging residues are generated during the harvesting operations and include stumps, roots, branches, and saw-dust. Wood processing residues arise from saw-mill and plywood processing operations and include discarded logs, barks, saw-dust and off-cuts (FAO, 1990). Data of annual production of round and processed wood for the year 2010 were obtained from the statistical abstract (UBOS, 2010a) and used to estimate the annual forest residue production. The procedure for estimating the energy potential of forest residues proposed by Smeets and Faaij (Smeets and Faaij, 2007) was used. The energy potential of logging residues was calculated using Equation 3.2,

$$Q_{HR} = \sum_{i=1}^{n} \left(W_i \times h \times LHV\right), \qquad (3.2)$$

where, Q_{HR} is the energy potential of logging residues and W_i is the annual production of round wood of category *i*. Factor, *h* is logging residue generation ratio and was assumed to be 0.6 (Smeets and Faaij, 2007; UBOS, 2010a). The energy potential of wood processing residue generated was estimated using Equation 3.3.

$$Q_{PR} = IRW \times p \times LHV \qquad (3.3)$$

where, Q_{PR} is the energy potential of wood processing residues and *IRW* annual consumption of industrial round wood. Factor, *p* is wood processing residue generation ratio. It is the fraction of logs that is converted into residues during the processing of wood and depends on the efficiency of sawmills. We used a *p* value for developing countries of 70 % (Howard and Stead, 2001). The *LHV* at 50% H_2O mass fraction was assumed to be 8 MJ kg^{-1} (McKendry, 2002a).

3.2.3 Sources of data

Annual production of crops, woody biomass, livestock and human population data used for the study were obtained from various sources. Food crop production data were obtained from volume IV of the Uganda census of agriculture 2008/2009 (UBOS, 2010b). The report presents data that was collected from all the districts of Uganda through a nationwide census. Procedures used in the census followed generally standard scientific methods. The methodologies used for sample design, enumeration plan, data processing and analysis are well explained in volume II of Uganda census on agriculture 2008/2009 (UBOS, 2010c). Production data for coffee, cotton and sugarcane were obtained from reports in references (UBOS, 2009), (CDO, 2009) and (USCTA, 2009), respectively. Livestock data was obtained from the summary report of the national livestock census of the year 2008 (UBOS/MAAIF, 2009), which gives an estimate of livestock numbers in all the districts of Uganda. Human population data used in the study were obtained from the 2009 statistical abstract (UBOS, 2009) and wood production data from the 2010 statistical abstract (UBOS, 2010a). To estimate the quantity of residues generated, the residue-to-product ratio (RPR) method was used. The RPR values of different crops and their respective heating values were obtained from published literature. This also applied to heating values of biomass residues and biogas generated from animal manure.

3.3 Results

3.3.1 Potential of crop residues

The energy potential of crop residues is given in Table 3.1. Crop residues represent a gross energy potential at 100% efficiency of about 150 PJ y^{-1}. The results show that maize residues have the highest energy potential of about 65 PJ y^{-1} followed by banana and beans residues, each with 16 PJ y^{-1}. Secondary residues in Table 3.1 include corn cobs, rice husks, coffee husks and bagasse. The total energy potential of the secondary residues is approximately 10 PJ y^{-1}, representing about 7% of the total crop residue potential.

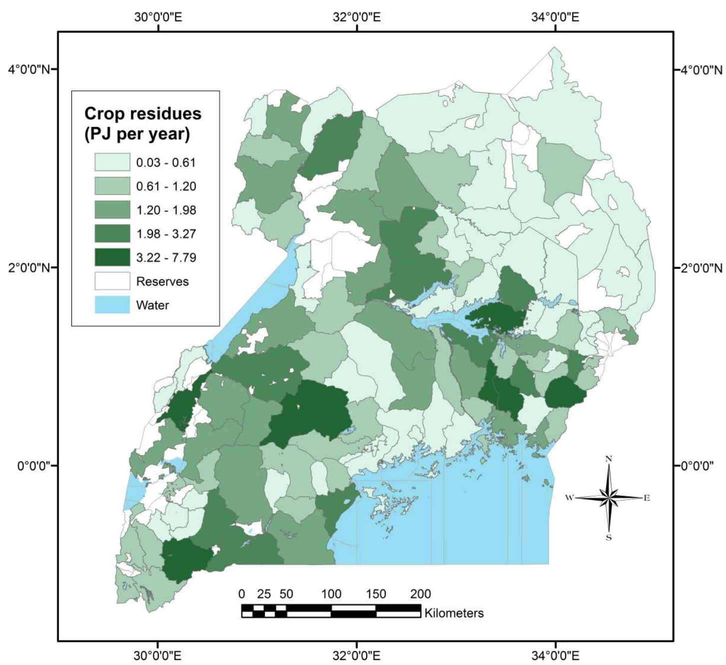

Figure 3.1. Distribution of the theoretical energy potential of crop residues in Uganda

Table 3.1. Theoretical energy potential of crop residues in Uganda

Crop produced	Annual crop production (kt)	Type of residue	H_2O mass fraction (%)*	Residue to product ratio (RPR)	Quantity of residues (kt)	Lower heating value (LHV) ($MJ\ kg^{-1}$)[a]	Energy potential ($PJ\ y^{-1}$)
Maize	2363.00	stalk	15.00	2.00	4726.00	16.30	65.50
		cobs	8.70	0.27	638.01	12.60	7.40
Millet	263.59	straws	15.00	1.40	369.03	13.00	4.00
Sorghum	373.34	stalk	15.00	1.40	522.68	13.00	6.25
Rice	189.18	straws	10.00	0.45	85.13	8.83	0.97
		husks	13.30	0.23	0.00	12.90	0.58
Beans	928.87	trash	4.50	1.40	1300.42	14.70	16.44
Groundnuts	244.58	trash and shells	8.20	2.10	513.62	11.20	5.33
Banana	4297.07	stalk and peels	85.40	2.00	8594.14	13.10	16.44
Cassava	2893.74	stems and peels	20.00	0.40	1157.5	13.10	7.58
Sweet potato	1817.66	vines and peels	20.00	0.40	727.06	16.00	9.31
Pigeon peas	10.90	stems	20.00	1.40	15.26	12.80	0.20
Soybean	23.12	trash	15.00	2.66	61.5	18.00	1.11
Sesame	97.80	trash	5.50	2.00	195.6	15.50	3.03
Sugar	197.37	bagasse	50.00	0.25	49.34	15.40	0.38
		tops	50.00	0.32	3.16	15.80	0.50
Coffee	211.76	husks	15.00	1.00	211.76	15.90	2.86
Cotton	23.18	stalks	9.30	2.10	48.68	15.90	0.75
Total							**148.67**

The energy potential of crop residues for Uganda was analysed and presented spatially using geographical information system (GIS) as illustrated in Figure 3.1. The map excludes the energy potential of residues of coffee; cotton and sugarcane because the available data did not provide production statistics for these crops in each district. The figure shows that there is regional variation in the energy potential of crop residues. Mubende district in the central region exhibited the highest crop residues energy potential of about 8 PJ y^{-1}, followed by Iganga at about 7 PJ y^{-1}, while Kampala had the lowest potential of 30 TJ y^{-1}. Other districts with crop residue energy potential of more than 4 PJ y^{-1} include Tororo, Kabarole, Luuka, Serere and Ntungamo.

3.3.2 Potential of animal manure

The energy potential of animal residues in Uganda is given in Table 3.2, including the potential to produce biogas from human manure. The results show that the total energy potential of animal residues amounts to about 65 PJ y^{-1}. In the year 2008, the country had about 11.7 million heads of cattle producing manure with an energy potential of 45 PJ y^{-1}, followed by goats with a potential of 9 PJ y^{-1}.

Table 3.2. Theoretical energy potential of animal manure

Animal category	Population (millions)	VS* (kg d^{-1})	B_o** (m^3 kg^{-1})	Potential (PJ y^{-1})
Cattle	11.71	2.67	0.20	45.64
Goats	12.29	0.33	0.31	9.18
Sheep	3.58	0.30	0.31	2.43
Pigs	3.18	0.59	0.30	4.25
Chicken	37.58	0.02	0.18	0.99
Ducks	1.47	0.02	0.22	0.05
Human	30.66	0.06	0.20	2.69
Total				**65.23**

* Volatile solids per animal
** Biochemical methane potential

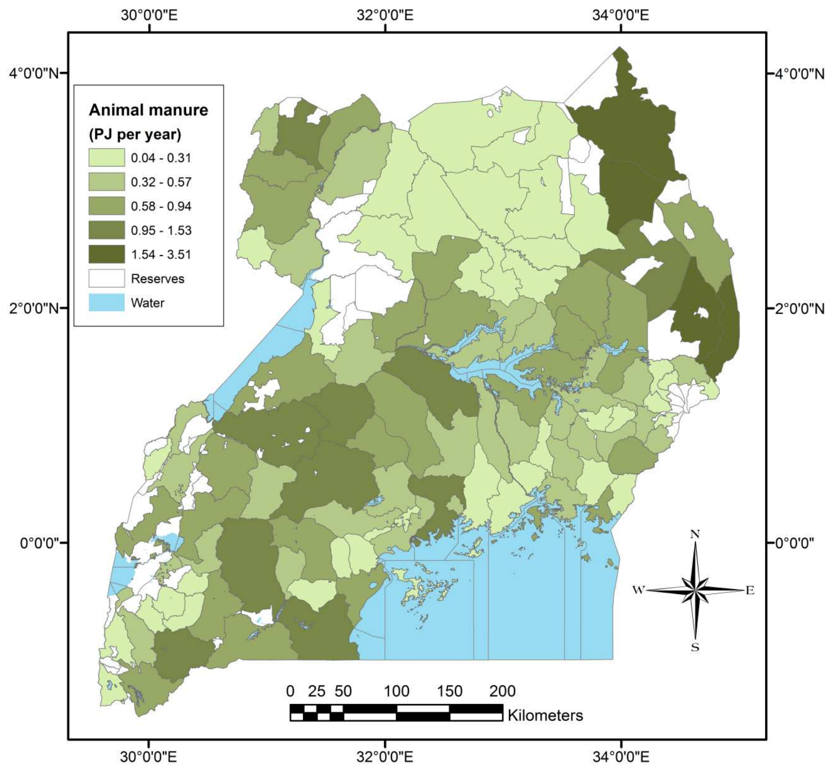

Figure 3.2. Distribution of the theoretical energy potential of animal manure in Uganda

The spatial distribution of the energy potential of animal manure in Uganda is given in Figure 3.2. The distribution is characterised high potential along a corridor from the south-west to the north-east of the country. The corridor is known to have a high density of cattle in Uganda and is generally referred to as the *cattle corridor* (Mulumba and Kakudidi, 2010). Kotido district reported the highest energy potential from manure of 3.5 PJ y^{-1}. Other districts with more than 2 PJ y^{-1} include Nakapiripirit, Kaabong, and Amodat.

3.3.3 Spatial distribution of crop and animal residues potential

The spatial distribution of the combined energy potential of crop and animal was analysed using GIS and presented spatially, as shown in Figure 3.3. Mubende district reported the highest overall biomass residue energy potential of 9 PJ y^{-1}, followed by Iganga and Ntungamu at 8 PJ y^{-1} and 7 PJ y^{-1}, respectively. Other districts with residue energy potential of at least 5 PJ y^{-1} include Luuka, Serere, Kabarole and Tororo.

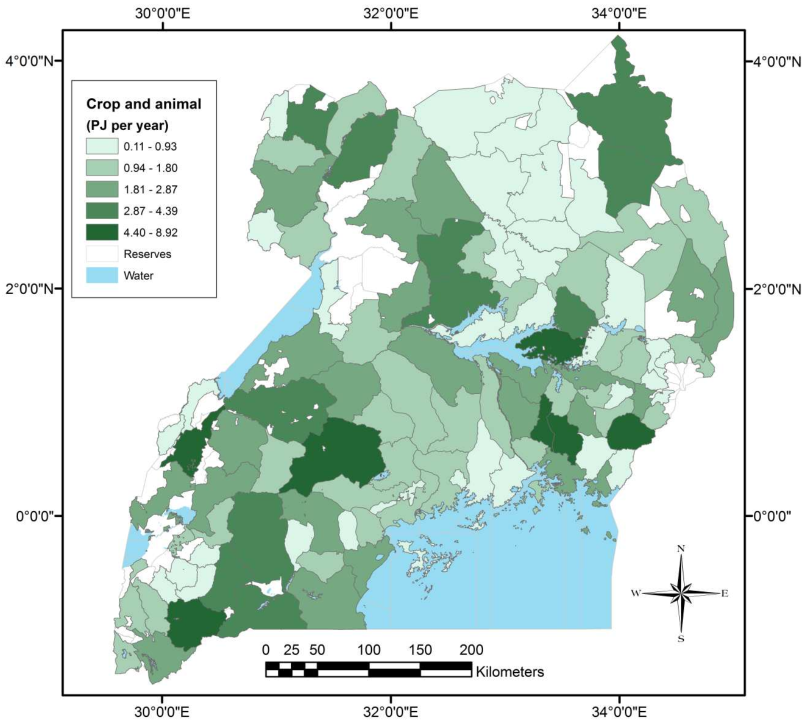

Figure 3.3. Distribution of combined the theoretical energy potential of crop residues and animal manure

The compositions of the residues in the different districts of the country were analysed using GIS and presented spatially as illustrated in Figures 3.4 to 3.7. Figure 3.4 shows biomass residue composition in northern region. It shows that the north-eastern part of the region is predominated by cattle manure while crop residue potential is very low. However most of the districts in the region do not have a single source of residue exceeding over 50 % of the energy potential, though maize and beans residues are more prominent. Figure 3.5 is an illustration of the composition of biomass residues in eastern region. It shows that maize residues are dominant in this region followed by banana residues. Central region, shown in Figure 3.6 has residues energy potential predominated by maize, cattle manure and banana. Cattle manure is more prominent in the northern part of the region while maize is predominant in mid central region. Finally, the western region is majorly rich in banana residue, which is more prominent in the southern part of the region and maize residues in the northern part, as illustrated in Figure 3.7.

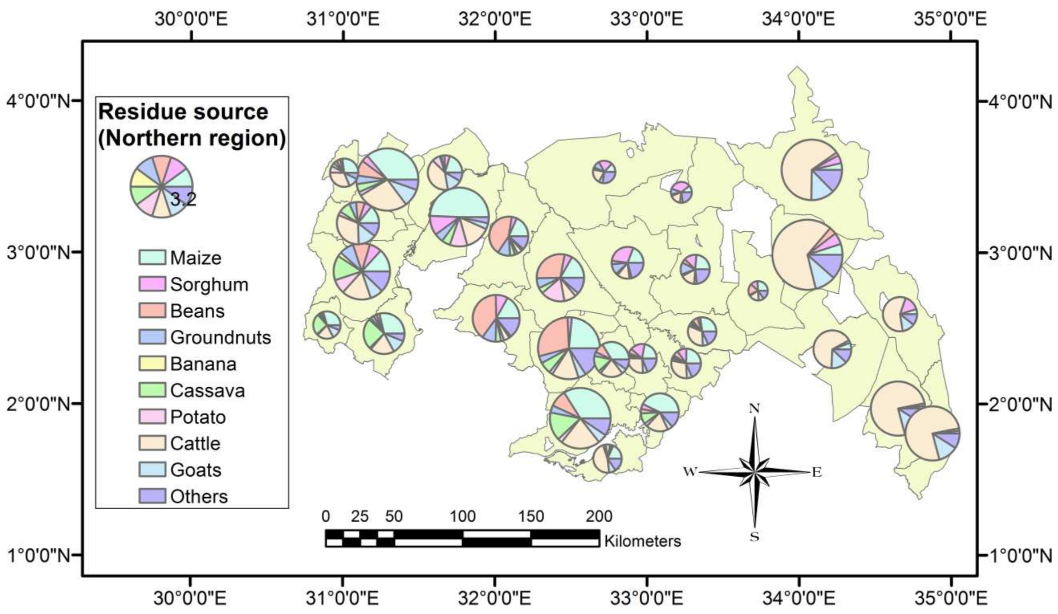

Figure 3.4. Composition of biomass residue in Northern Uganda

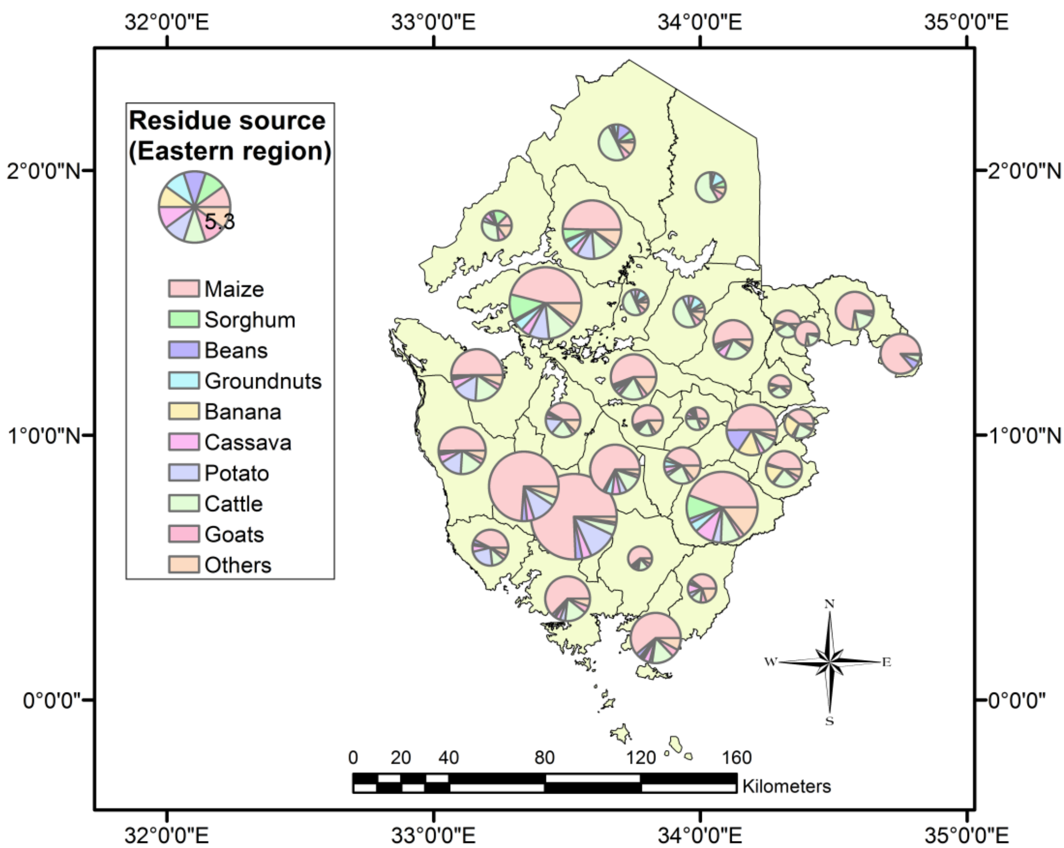

Figure 3.5. Composition of biomass residue in Eastern Uganda

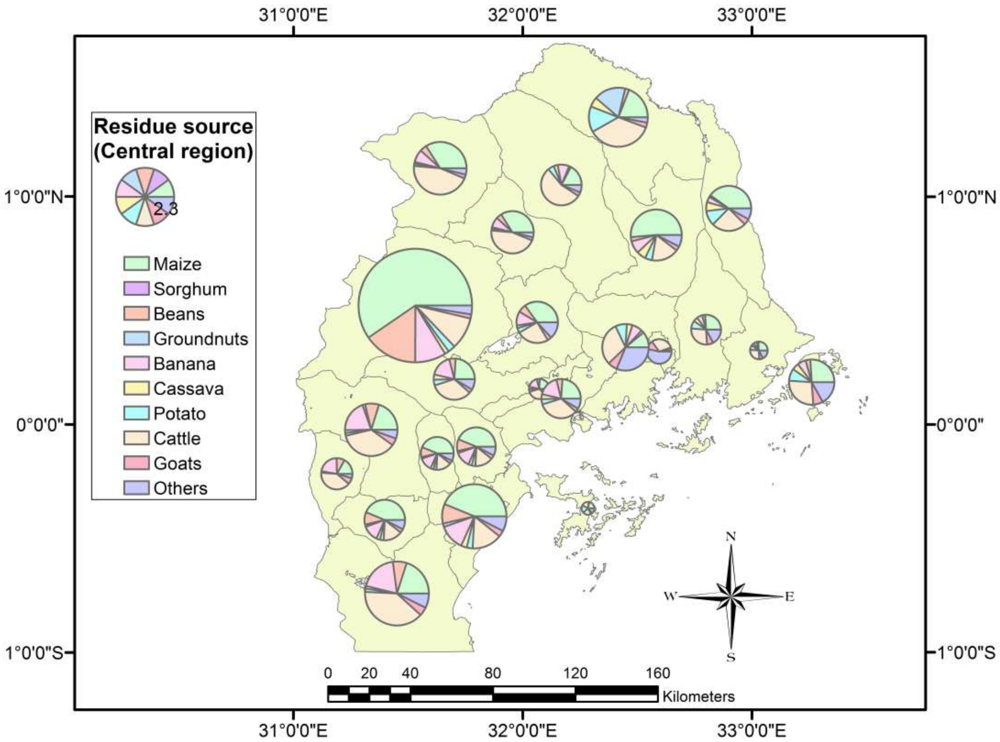

Figure 3.6. Composition of biomass residue in Central Uganda

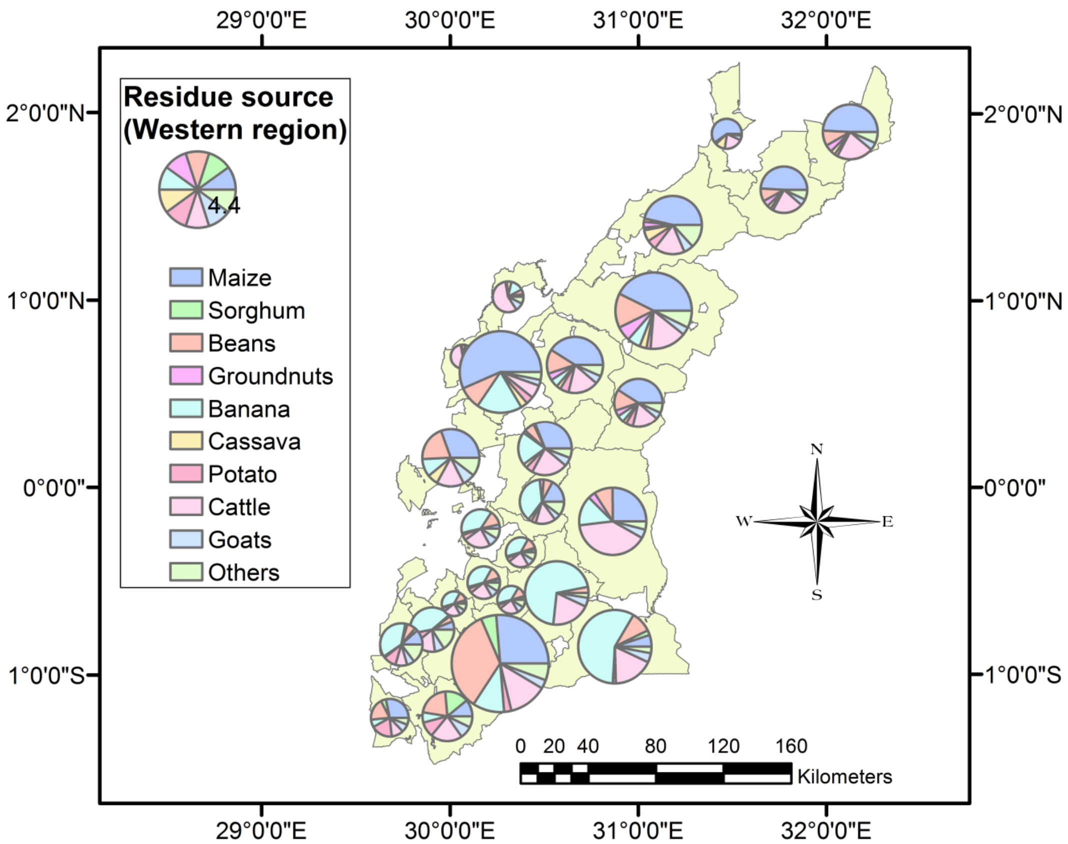

Figure 3.7. Composition of biomass residue in Western Uganda

3.3.4 Potential of forest residues

Results of energy potential of forest residues are presented in Table 3.3. In this study, forest residues were categorised as logging and processing residues. Results show that about 5.0 kt y^{-1} of forest residues are generated during logging operations. The processing residues are however much less corresponding to about 0.35 kt y^{-1}. In terms of energy potential, residues from firewood production has the highest potential of about 20 PJ y^{-1}, followed by charcoal production at about 17 PJ y^{-1}. The total energy potential of forest residues in Uganda is estimated at about 44 PJ y^{-1}.

Table 3.3. Theoretical energy potential of forest residues

Wood category	Quantity (Mt y^{-1})*	Logging residues	Processing residues	Total residues (Mt y^{-1})	Energy potential (PJ y-1)
Sawn timber	1027	308.10	359.45	667.55	5.34
Poles	888	266.40	-	266.40	2.13
Firewood fuel	5088	2526.40	-	2526.40	20.21
Charcoal fuel	6963	2088.90	-	2088.90	16.71
Total					**44.39**

* Source: UBOS, (2010a)

3.3.5 Total energy potential

Table 3.4 gives a summary of the energy potential from the sources analysed in this study. The total energy potential from all the sources studied is about 260 PJ y^{-1}. The overall result shows that crop residues exhibit the highest energy potential of about 150 PJ y^{-1}. Therefore, crop residues alone contribute over 50% of the overall energy potential of biomass residues in Uganda.

Table 3.4. Total energy potential of residues

Source of energy	Energy potential (PJ y^{-1})
Crop residues	148.67
Animal residues	65.23
Forest residues	44.39
Total	**258.29**

3.4 Discussions

In this study, we evaluated the energy potential of agricultural and forest residues in Uganda and the findings indicate that the total potential is about 260 PJ y^{-1}. This is close to 70% of the total biomass energy requirements for Uganda in the year 2008, which was estimated at about 385 PJ (MEMD, 2008). Crop residues exhibited the highest theoretical energy potential of about 150 PJ y^{-1}. However, it is important to note that the accuracy of the estimated energy potential of biomass residues may be subject to errors that are inherent during the collection of census data (Elmore et al., 2008), and seasonal variation in production levels. According to volume IV of the Uganda census of agriculture (UBOS, 2010b), the estimates in crop production had a coefficient of variation of 20%. This suggests that the estimates in energy potential could be subject to similar levels of accuracy. The energy potential reported here are gross values at 100% efficiency. The actual implementation potential is determined by several factors including economic, social, environmental, and institutional and policy incentives. Logistical considerations, infrastructural and technological constraints as well as availability of skilled personnel are other factors that determine the implementable potential.

3.4.1 Recoverability of potential of agricultural residue

Recoverability of agricultural residues is determined by the type of residues; need to retain some residues to maintain the quality of agricultural soils amongst other factors. Generally, crop residues are classified as primary and secondary residues. Primary residues are generated during harvesting and primary processing of the crops in farms and crop plantations. The residues are normally scattered over a large geographical area, therefore presenting a major logistical challenge for their collection for energy application. Primary residues are usually in a loose form and may require bailing or densifying in order to improve their collection and utilisation efficiency. For developing countries like Uganda, provision of the necessary equipment and skilled personnel for collection of loose biomass may present a challenge. Another important consideration is that residues perform ecological functions like providing soil nutrients, control of soil erosion and some fraction should therefore be left in the fields (Govaerts et al., 2006). The amount of primary residues that can be realistically harnessed is estimated using recoverable fraction of biomass. The actual values of recoverable fraction of biomass residues for different crops have been estimated and reported in literature (Cornelissen et al., 2012; Haberl et al., 2010) and may vary from 19 % to 75 %.

Secondary residues on the other hand are generated during secondary processing of agricultural produce in large quantities at specific locations. Common examples in

Uganda include coffee husks, rice husks and bagasse. These residues have other applications, for example, coffee husks are frequently used as bedding material in poultry housing. However, secondary residues are generally considered to be problematic to agricultural processing industries because of costs incurred in their disposal. As a result, many agricultural processing facilities in Uganda burn the secondary residues in open air near the agro-processing facility, therefore presenting serious environmental problems.

3.4.2 Recoverability of animal residues

Results show that annual energy potential of animal manure is about 65 PJ y^{-1} with cattle manure having the highest contribution of about 45 PJ y^{-1}. The current government policy targets cattle manure for biogas production, with a target of installing 100,000 domestic biogas digesters based on cattle manure by the year 2017 (MEMD, 2007). The findings of this study seem to support this policy since cattle manure has the highest energy potential amongst the animal manure. However, it should be noted that there are several factors that influence the actual implementation potential of the animal residues. First, a large percentage of cattle in Uganda are reared in districts with highest potential are under pastoralism system, therefore posing constraints due to difficulty in collecting the manure. Normally, domestic biogas technology common in developing countries is best suited for zero-grazing systems because it reduces the constraints of manure collection. Also, the systems usually require large quantities of water, which is often a challenge to access in many cattle producing areas of Uganda. It should also be noted that human manure has a potential to produce 2.69 PJ y^{-1}. Some of the energy potential could be harnessed in public institutions such as schools, hospitals, and universities.

3.4.3 Recoverability of forest residue

The study showed that the energy potential of forest residues is about 44 PJ y^{-1}. Forest residues are generally classified as logging residues and processing residues. Logging residues are generated during logging operations, which usually take place in geographically sparse locations making it difficult to collect the residues for energy utilisation. There are also technical, ecological and environmental considerations that limit the quantities of forest residues that can be practically recoverable for energy. For example, it may be difficult to recover stumps and roots in many developing countries due to technological constraints. Environmental considerations also require that the stamps and roots are not harvested since they provide soil stabilisation function. The amount of logging residues that can be practically harvested is estimated using logging residue recoverability fraction. This is the fraction of the generated logging residues that can be realistically harvested for energy application and is estimated to be about 25% in developing countries (Yamamoto et al., 1999). Residues are also generated during processing of wood and are estimated using wood processing residue recoverability fraction. Available literature indicates that up to 42 % of wood processing residues can be recovered from saw mill in developing countries for energy application (Yamamoto et al., 1999).

3.4.4 Economic, social and environmental considerations

Sustainable utilisation of biomass residues for energy depends on a number of factors including economic, social and environmental considerations. The cost of the logistical operations for energy conversion of biomass residues has been identified as one of the major bottlenecks in their utilisation. This is because of the complex supply chains usually involved (Iakovou et al., 2010). Economic aspects greatly depend on the cost associated with the collection, transportation, storage and processing of residues. These costs are influenced by specific site conditions, availability of biomass and supply chain design, investment and operational costs (Batidzirai et al., 2006). The logistics for biomass residue utilisation may be influenced by the biomass distribution density, operating scale and window, relative distance to supply destination, and the characteristics of the energy conversion technology employed. Usually, use of residues for energy entails gathering of residues from point of generation and transportation to processing facility. This is followed by pre-treatment processes such as size reduction, drying densification and transportation to market. Other considerations that may influence the economics of the system include availability of infrastructure, geographical location of the area, regulatory environment and competition with other fuels. However, despite these complexities, Skoulou and Zabaniotou (Skoulou and Zabaniotou, 2007) noted that use of biomass residues can be economically viable when the logistics is carefully planned in combination with well established energy technologies, more so in the error of increasing fossil fuel prices.

The importance of social aspects in development of bioenergy systems is another consideration that is emphasised in the recent past. Development of suitable systems for biomass residue utilisation will therefore have to involve stakeholders such as potential investors, end users, regulators and decision makers. Environmental aspects should also be taken into account when designing systems for utilising biomass residues for energy. One of the main environmental benefits of utilising biomass residues is the reduction in net CO_2 emission to the atmosphere, therefore contributing to reduction of global warming. A detailed discussion social, economic and environmental consideration in renewable energy sector is given in Akella et al., (2009).

3.4 Conclusions

The energy potential of agricultural and forest residues in Uganda has been evaluated and the spatial distribution presented. The study showed that the country has a gross energy potential from biomass residues equivalent to 70% of the gross biomass energy requirements for the year 2008. However, use of biomass residues for energy application is still limited in the country. For successful utilisation of biomass residues in the country, a number of technical, environmental, social and economic constraints need to be overcome. It is therefore recommended that detailed studies involving sustainability analysis of biomass residue utilisation for energy is carried out by integrating technical, economic, environmental and social considerations in a decision framework. In conclusion, Uganda has enormous potential to generate energy from biomass residues. When exploited in a sustainable manner, biomass residues could contribute to reduction in deforestation and environmental degradation in the country.

PART II

Development and application of sustainability assessment methodology in Uganda

Chapter 4 – Sustainability assessment framework

Summary

In this chapter, a sustainability assessment framework for bioenergy systems in developing countries was proposed. The chapter begins with an introduction to the concept of sustainability assessment, followed by a succinct review of relevant literature on sustainability assessment methods. Methods proposed for assessing sustainability of bioenergy systems in developing countries was selected and justification of choices given. This was followed by presentation of the proposed sustainability assessment framework. The proposed method incorporates social, economic, environmental and technological aspects of bioenergy systems using multi-criteria decision analysis. This chapter gives explanation of steps required to conduct a sustainability assessment of bioenergy systems following the proposed methodology.

4.1 Introduction

Sustainability assessment aims at helping policy and decision makers to select actions or policies that enhances the sustainability of the society (Pope et al., 2004). It was derived from the concept of sustainable development, which was defined by the Brundtland Commission as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (World Commission on Environment, 1987). By this definition, it is very difficult to rationalise the concept of sustainability in quantifiable terms.

To facilitate assessment, the sustainability concept has been broken down in to dimensions. The most commonly used dimensions for sustainability analysis are the social, economic and environmental aspects of the systems under analysis. These three dimensions are also called the triple bottom line (TBL). Other scholars however argue that there are more considerations than the TBL, for example Pawłowski, (2008) proposed a total of seven sustainability dimensions. To achieve sustainable development, decision makers should therefore aim at taking all the dimensions of sustainability into consideration while planning development projects. These results in conflicting objectives and therefore interests of multi-stakeholder groups have to be taken into account. This poses serious decision making challenge especially in developing countries where the concept of sustainability assessment is relatively new.

The cooking energy is one of the sectors with the highest sustainability challenges in developing countries. The aim of this chapter was therefore to propose a methodology to facilitate sustainable decision making in the selection of bioenergy systems for cooking in developing countries.

4.2 Review of sustainability assessment methods

Currently, there are a variety of tools for sustainability assessment. The tools can be broadly classified as monetary, indicators, biophysical and integrated (Gasparatos and Scolobig, 2012; Ness et al., 2007) as summarised in Figure 4.1. Choice of a given tool depends on the objectives of the assessment.

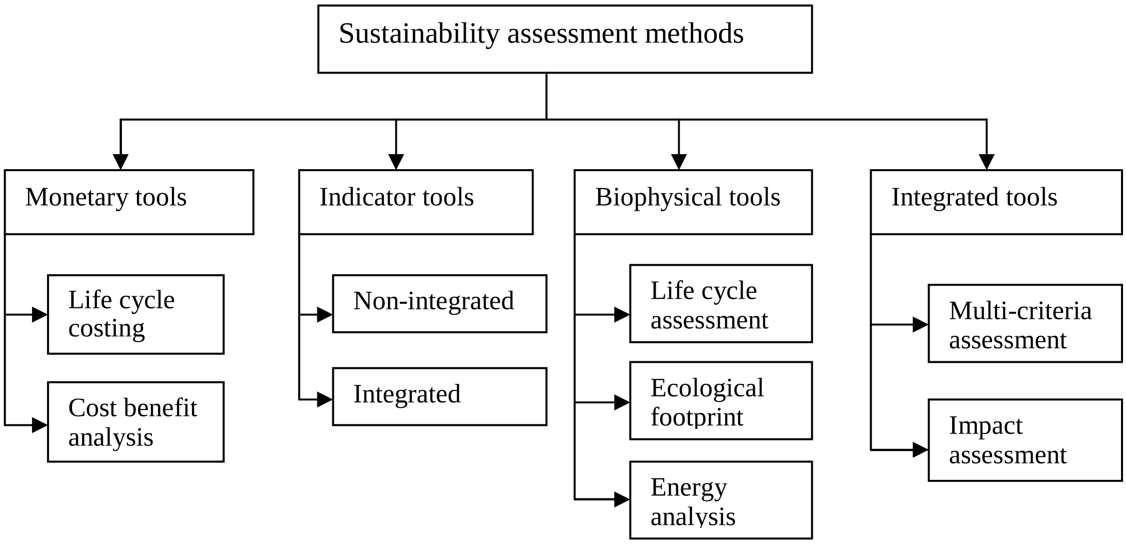

Figure 4.1. Overview of sustainability assessment methods. Developed based on Gasparatos and Scolobig, (2012) and Ness et al., (2007).

4.2.1 Indicator based methods

Indicator-based sustainability assessment tools apply a set of criteria and indicators. The indicators are used as a measure of sustainability and can be integrated (also called composite indices) or non-integrated. They are intended for assessing the socio-economic and environmental sustainability at a national or regional level (Ness et al., 2007). The choice of indicators can include the social, economic and environmental dimensions of sustainability. Indicator-based methods are useful for assessing complex systems and results can be used for policy decisions and communicating about sustainability of projects to the public (Buytaert et al., 2011).

A number of bioenergy certification schemes use non-integrated indicator-based method for assessing sustainability. Examples include the Round Table on Sustainable Palm Oil, Renewable Transport Fuels Obligation and the Global Bioenergy Partnership. Other examples of indicator based tools are given in Labuschagne et al., (2005), Scarlat and Dallemand, (2011) and Singh et al., (2009).

Integrated indices use composite indicators as a measure of sustainability at national or regional levels. Examples of composite indicators include human development indices such as the human development index and human poverty index developed by UNDP. In the field of bioenergy, Mainali et al., (2014) recently developed an integrated index for assessing progress toward sustainable development of energy at national level. Mata et al., (2013) also used composite indicators as a tool for assessing sustainability of fuel supply chains.

4.2.2 Biophysical methods

There are several biophysical methods, but the most commonly used are the life cycle assessment (LCA), material flow analysis (MFA) and energy analysis. The LCA method is a well-developed method and is widely used to evaluate environmental impacts of products or services from a life cycle perspective; that is, from cradle-to-grave. Currently there are International Standard Organisation (ISO) standards to guide LCA studies. The ISO 14040 standard (ISO, 2006a) provides the principles and framework, while ISO 14044 standard (ISO, 2006b) gives requirements and guidelines for LCA studies. The LCA method is perhaps the most popular bioenergy sustainability assessment method, with several applications available in literature, examples include Jorquera et al., (2010) and Buonocore et al., (2012).

Ecological footprint (EF) is another biophysical sustainability assessment method that can be used for analysis at national, regional or project scales. Wackernagel and Monfreda, (2004) defined EF as the amount of bio-capacity required by a population, organisation or process to produce its resources and absorb waste using prevailing technologies. The analysis mainly focuses on estimating direct and indirect land requirements for producing a given quantity of product or service (Finnveden and Moberg, 2005). Examples of studies that used EF method for assessing sustainability of energy systems include Holden and Høyer, (2005), Stöglehner, (2003) and Stoeglehner and Narodoslawsky, (2009).

Material flow analysis is a biophysical sustainability assessment method used to analyse material flows at national levels (Bringezu et al., 2003). It aims at supporting dematerialisation and minimising losses of resources (Ness et al., 2007). The methods can be divided into analysis of total material requirement, material intensity per unit service and substance flow analysis. Emphasis is mainly placed on flows of input materials (Finnveden and Moberg, 2005).

Energy analysis is based on the first law of thermodynamics and aims at analysing energy flows at the level of an economy. The analysis can entail different measures of energy such as available energy or *exergy* (Saidur et al., 2012) and embodied solar energy or *emergy* (Zhang and Long, 2010). It aims at evaluating areas where there are wastage of resources and thus helping in the design possible efficiency improvement strategies. Liao et al., (2011) is a example of sustainability assessment applying both emergy and exergy analyses on biofuel systems.

The shortcoming of the biophysical methods is that they do not adequately address the social and economic dimensions of sustainability. Their main emphasis is on the biophysical environment. Therefore, biophysical tools do not adequately suit sustainability assessment of bioenergy systems since they do not address the social and economic aspects.

4.2.3 Monetary methods

There are a wide variety of monetary tools, most of which originate from the economic literature. Here, only the cost benefit analysis (CBA) and life cycle costing (LCC), which are commonly applied in analysis of sustainability of bioenergy systems are discussed.

Cost benefit analysis is one of the monetary sustainability assessment tools originating from welfare economics. The tool is useful for appraising projects or policies on the basis of the comparison of total project costs and anticipated project benefits (Buytaert et al., 2011). Anticipated benefits are usually estimated by the beneficiaries' "willing-to-pay" for the benefits, while costs are assessed through losers' "willingness-to-accept" them (Gasparatos et al., 2008). Examples of biomass energy studies using cost benefit analysis include studies by Wiskerke et al., (2010), Uellendahl et al., (2008) and Menegaki, (2008). Difficulty in estimating costs and benefits of the actions are the main challenges of the CBA method.

Life cycle costing (LCC) is an economic approach for estimating the total incremental cost of a product or service right from inception through to its end of life (Asiedu and Gu, 1998). The traditional LCC is used for ranking projects for investment decision making (Ness et al., 2007). Currently, there are a large number of variants of LCC, including full cost accounting, full cost environmental accounting and life cycle cost assessment. Gluch and Baumann, (2004) gives a comprehensive review of the LCC methods. Examples of studies using the LCC method for analysing biomass energy systems include Silalertruksa et al., (2012) and Luo et al., (2009).

4.2.4 Integrated assessment methods

Integrated assessment methods holistically consider the TBL aspect of sustainability. Several integrated assessment method are available, and examples are given in Ness et al., (2007). In this study, environmental impact assessment and multi-criteria decision analysis are discussed since they are amongst the most popular.

Environmental impact assessment (EIA) was developed to identify and predict the impacts of a project on the biophysical and human and environment (Noble, 2011). It aims at identifying the negative impacts prior to the implementation of a project therefore allowing for incorporating measures to avoid or mitigate them. The EIA is an integrated method that incorporates social, economic and environmental dimensions of sustainability (Ness et al., 2007). One important aspect of EIA is that it allows for public participation in the process, therefore allowing for democratic decision making. However, the EIA method is limited in its ability to consider alternatives, since it is applied to projects that are already well in advanced stages (Pope et al., 2004).

Multi-criteria decision analysis (MCDA) is a branch of operational research models and is suitable for solving complex decision problems with multiple objectives and criteria. The MCDA methods are suitable for analysing problems characterised by conflicting criteria and incommensurable units.

Multi-criteria decision methods have a number of advantages over other methods discussed in this section. The methods improves transparency and accountability in the decision making process and the decision process can be audited at a later stage. By allowing stakeholders to state their preferences during the decision making process, areas of contention can be identified and addressed, therefore helping in conflict resolution

(Hajkowicz and Collins, 2007; Mutikanga et al., 2011). It can incorporate both qualitative and quantitative data, making it possible to investigate and integrate interests of different actors in the decision making process (Mateo, 2012). These advantages make MCDA methods well suited for decision making in energy sector, which requires that the social, economic, environmental and technical dimensions are taken into consideration (Nzila et al., 2012; Wang et al., 2009). The MCDA method was therefore chosen for the development of the decision making framework for assessing the sustainability of bioenergy systems in developing countries.

4.3 An overview of multi-criteria decision analysis

4.3.1 Overview of the MCDA procedure

The objective of a MCDA study is to identify the best compromise action out of a finite set of alternatives on the basis of a given set of evaluation criteria. Mathematically, a multi-criteria decision problem can be expressed using Equation 4.1 (Brans, 2002) as:

$$\max\left\{f_1(a), f_2(a), \cdots, f_j(a), \cdots, f_k(a) \middle| a \in A\right\} \tag{4.1}$$

where, A is a set of n alternative actions to be ranked on the basis of k evaluation criteria: $f_1(\cdot)$, $f_2(\cdot)$, …, $f_j(\cdot)$, …, $f_k(\cdot)$. Parameters $f_j(a)$ is the evaluation or score of alternative, a based on criterion $f_j(\cdot)$.

The main steps in MCDA include problem identification and structuring, development of evaluation matrix, preference assessment, assignment of weights to criteria, aggregation of result to rank alternatives and sensitivity analysis. The steps are illustrated diagrammatically in Figure 4.2. The problem structuring phase involves recognition of a need and developing objectives for their fulfilment. Then alternative actions are generated and suitable criteria for their evaluations are identified. Alternatives and criteria are entered in the two-way evaluation matrix as illustrated in Table 4.1. Each alternative is evaluated on the basis of all the criteria and the evaluations, $f_j(a)$ are included in the table. At this stage, the evaluations have different units and may be on ordinal or cardinal scales. In order to make them commensurable, value assessment using preference functions is carried out using appropriate functions. This transforms the evaluations into perceived value or preference of a decision maker on a scale, usually ranging from 0 to 1 (or 1 to 100).

Table 4.1. Two-way multi-criteria evaluation matrix

Alternatives	**Criteria**					
	$f_1(\cdot)$	$f_2(\cdot)$		$f_j(\cdot)$		$f_k(\cdot)$
a_1	$f_1(a_1)$	$f_2(a_1)$	…	$f_j(a_1)$	…	$f_k(a_1)$
a_2	$f_1(a_2)$	$f_2(a_2)$	…	$f_j(a_2)$	…	$f_k(a_2)$
…	…	…	…	…	…	…
a_i	$f_1(a_i)$	$f_2(a_i)$	…	$f_j(a_i)$	…	$f_k(a_i)$
…	…	…	…	…	…	…
a_n	$f_1(a_n)$	$f_2(a_n)$	…	$f_j(a_n)$	…	$f_k(a_n)$

Meanwhile, the criteria are usually considered to have different influences on the final decision, therefore they should be assigned weights corresponding to their perceived relative importance. The transformed evaluations are then aggregated to derive the ranks of the alternative. The last step is sensitivity analysis, which helps to evaluate the robustness of the results to changes in weights of criteria. An explanation of the MCDA procedure is given by Geneletti, (2005).

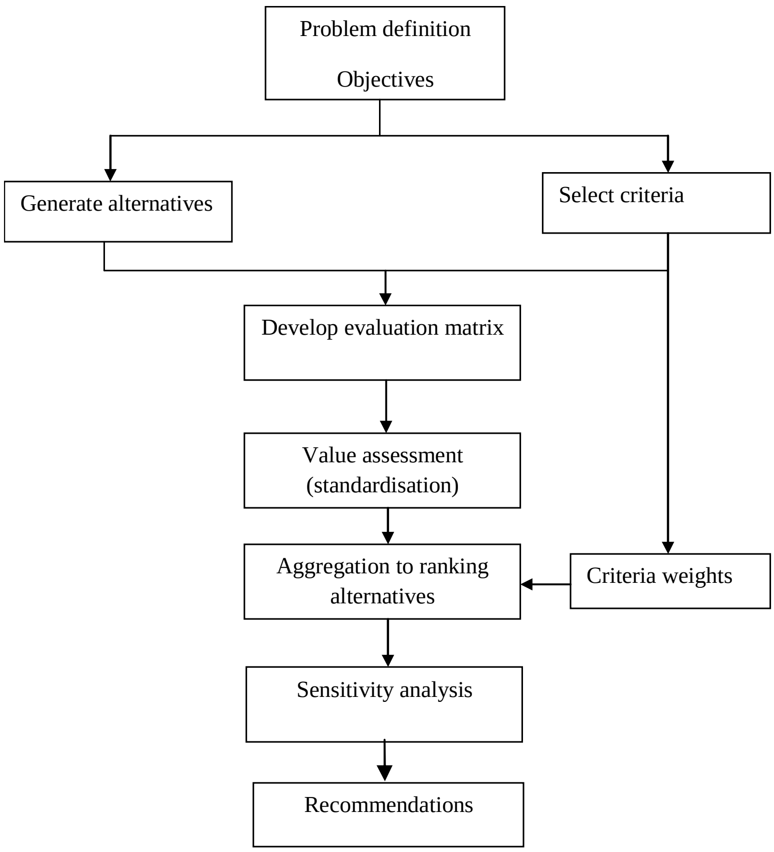

Figure 4.2. Work flow of the MCDA process, modified from Geneletti, (2005)

4.3.2 Overview of MCDA methods

Over the years, several MCDA have been developed. They can be broadly classified into value measurement models, goal aspiration and reference models, and outranking models (Cavallaro, 2010; Løken, 2007).

Evaluation of a MCDA problem using value measurement models, also called the "American School" results in numerical scores assigned to each alternative. The scores determine the preference order of the alternatives; and the alternative highest score is preferred over others. These models are known to be simple and user friendly (Løken, 2007). Examples of MCDA methods based on value measurement models include the analytical hierarchy process (AHP), simple multi-attribute rating technique, utilities additives, and the MACBETH methods (Cavallaro, 2010).

Goal aspiration and reference models, also called goal programming models aims at finding alternatives which most closely fulfil a pre-determined set of goals or aspiration levels (Løken, 2007; Mendoza and Martins, 2006). The models can be used as a filtering tool at an early stage of planning when there are many alternatives. Examples include the technique for order performance by similarity to ideal, the method of displaced ideals, and the step method (Løken, 2007).

Outranking methods are also called the "French School" involves pairwise comparison of alternatives, to check which of them is preferred over the other on the basis of each criterion. Ranking is based on the degree of outranking of an alternative over others. An alternative, *a* is considered to outranks *b* when there are adequate arguments that "*a* is at least as good as *b*" when all criteria are taken into consideration. Methods that use outranking models include ELECTRE, PROMETHEE, ORESTE and REGIME (Cavallaro, 2010).

4.4 Conceptual framework of the proposed methodology

The conceptual framework of the proposed bioenergy sustainability assessment method is illustrated in Figure 4.3. The method assumes that sustainability of a given bioenergy technology is measured by the relative deviation from that of a reference system. A positive deviation means the new technology is more sustainable and therefore desirable. Negative deviations implies that the technology will lead to a decline in sustainability and therefore not desirable. The method was developed by incorporating the capacity of different sustainability assessment methods into a decision framework. It incorporates biophysical and monetary methods of sustainability assessment, as well as social and technological aspects. The framework also allows for participation of stakeholders both from the inception and the decision making phase.

Phase 1: Preliminary assessment and problem structuring

This phase consists of situation analysis, resource assessment and structuring the sustainability assessment problem. During situation analysis, information on bioenergy technologies used in the target area should be analysed. This could be through a combination of literature review and field visits. Stakeholders in the bioenergy sector should be identified at this stage. Stakeholders should be carefully classified into categories to ensure that important groups are not omitted from representation in the decision making process. Legislative requirements and policy frameworks should also be reviewed at this stage. Information on the potential of biomass resources for energy use should be sourced. This will help in later stages when formulating bioenergy supply chains to be included in the sustainability analysis. Situation analysis and resource assessment for Uganda was conducted in this study and results given in Chapters 1 and 2, respectively.

Next, the structure of the decision problem is developed. This involves formulation of objectives of the study and development of alternatives to include in the assessment. Alternatives are formulated by taking into consideration possible technologies identified during the preliminary assessment stage. At this stage, as many alternatives as possible should be formulated, and a detailed description of each alternative developed. The most commonly used technology for cooking should be included in the analysis as a reference system. Where possible, samples should be collected for demonstration to stakeholders. Alternatively visual aids such as photographs, video clips could be used to demonstrate the proposed systems to stakeholders.

Phase 2. Pre-screening

The objective of this phase is to identify and eliminated trivial alternatives so that only few more promising alternatives are included in the more detailed phases of sustainability assessment. A participatory methodology for pre-screening using strengths, weaknesses, opportunities and threats (SWOT) analysis, AHP and desirability functions was developed. The SWOT analysis was selected because of its ease of use. The AHP method is also easy to use in a participatory setting and can convert results of SWOT analysis into quantifiable parameters. Detailed explanation on the proposed method, with an example is given in Chapter 5 and in Okello et al., (2014).

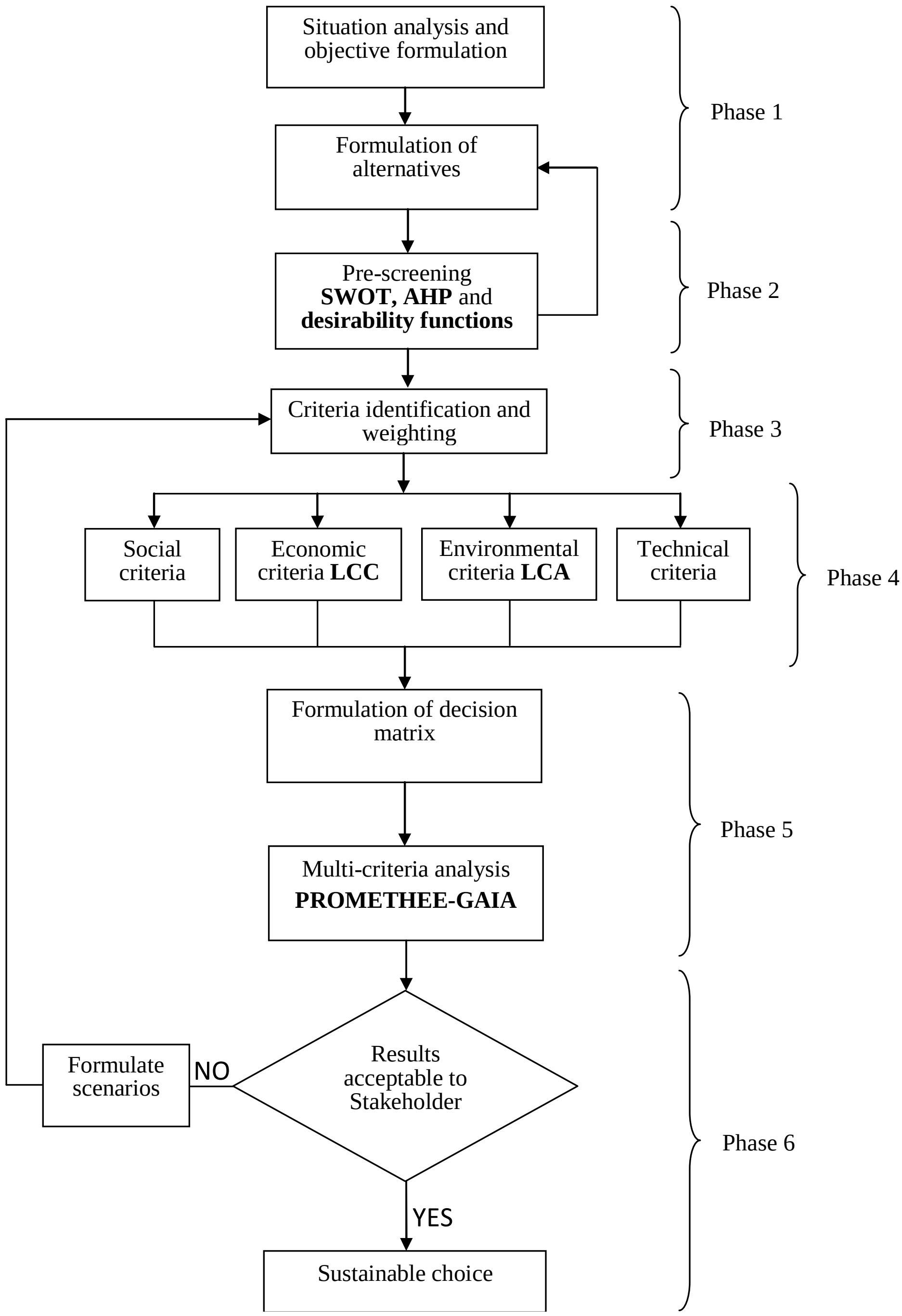

Figure 4.3. Proposed sustainability assessment framework for bioenergy cooking systems in developing countries

Phase 3. Selection and weighting of criteria

This stage aims at identifying suitable set of criteria for sustainability assessment and assigning weight to each of them basing on their relative importance. The proposed criteria selection method is a collaborative process between the decision analyst and a panel of multi-stakeholders of the bioenergy sector. The same composition of stakeholders developed in Phase 2 of the framework could be suitable. The analyst develops a comprehensive list of criteria based on available literature as well as consultation with stakeholders. This list then goes through a screening process based on a number of conditions. Weight can then be assigned to each of the selected criterion, using the AHP methodology. Detailed explanation on how this phase can be executed is explained in Chapter 6 of this thesis.

Phase 4: Evaluation of alternatives

During this phase, each alternative is evaluated on the basis of each criterion and assigned corresponding score $f_j(a)$ in multi-criteria evaluation matrix (Table 4.1). The evaluations could be in both ordinal and cardinal scales. Different methods of evaluation can be used, for example biophysical tools such as LCA could be used to evaluate the environmental criteria. Monetary tools such as LCC could also be used to evaluate economic aspects. There can be cases where it is not possible to quantify all the criteria; in such cases, expert judgement on ordinal scales, say from 1 to 5 as explained in Section 8.3.5 of this thesis could be employed. For this study, LCA was used to evaluate the environmental criteria of four energy systems. Detailed explanation of this method is given in Chapter 7 and additional information is provided in Section 8.3.

Phase 5: Aggregation and ranking of alternatives

This phase results in the actual analysis of the relative sustainability ranking of the alternative bioenergy systems under study. As a starting point, a multi-criteria evaluation matrix illustrated in Table 4.1 is developed, using information generated in Phases 3 and 4 above. Different MCDA models can then be used to carry out the ranking of the technologies. The outranking method, Preference Ranking and Organisation Method for Enhanced Evaluation (PROMETHEE) and Graphical Analysis for Interactive Aid (GAIA) methods were proposed. This is because the methods have a number of advantages over other MCDA methods. First, it has a simple analytical structure compared to other MCDA methods. The methods also have ability to identify cases of indifferences and incomparability in the ranking of alternatives. The GAIA tool has ability to retain a lot of information about the relationships between criteria and alternatives, which would otherwise be lost in other MCDA methods. The PROMETHEE-GAIA methods therefore enhance rational selection of the alternatives after the ranking phase. During this phase, scenario can be developed and evaluated. Sensitivity of the results to changes in the weight of the alternatives and preference functions can also be carried in order to gain more insight into the ranking of the technologies. A detailed example of the steps involved in Phase 4 is given in Chapter 8 of this thesis.

Phase 6: Decision making

In many developing countries, the users of bioenergy technologies are also responsible for provision the energy. This therefore means that stakeholders should take the final responsibility of decision making with the aid of the analyst. Where there is no consensus on the most suitable alternative at the end of Phase 4, a review of the process could be carried out from the criteria identification Phase as illustrated in Figure 4.3.

4.5 Conclusions

In this chapter, an integrated framework for assessing sustainability of bioenergy cooking systems used in developing countries was proposed. The framework is quite generic and could be applied in a variety of settings. It is hoped that implementation of this framework in the selection of cooking energy systems would greatly enhance sustainable development of developing countries.

Chapter 5 – Participatory appraisal of bioenergy technologies in Uganda

Parts of this chapter was published in *Energies* as;

Okello, C., Pindozzi, S., Faugno, S., Boccia, L., 2014. Appraising Bioenergy Alternatives in Uganda Using Strengths, Weaknesses, Opportunities and Threats (SWOT)-Analytical Hierarchy Process (AHP) and a Desirability Functions Approach. Energies. 7, 1171-1192.

Chapter 5 – Participatory appraisal of bioenergy technologies

Summary

Low levels of access to clean and reliable energy technologies is a major challenge to most developing countries. The decision to introduce new technologies is often faced by low adoption rates or even public opposition. Also, data required for effective decision making is inadequate or even lacking, thus constraining the planning process. In this study, a methodology for participatory appraisal of technologies, integrating desirability functions to the SWOT-AHP methodology was developed. Application of the methodology was illustrated with an example for participatory appraisal of four bioenergy technologies in Uganda. Results showed that the methodology is effective in evaluating stakeholder preferences for bioenergy technologies. It showed a high potential to be used to identify and rate factors that stakeholders take into consideration when selecting bioenergy systems. The method could be used as a tool for technology screening, or reaching consensus in a participatory setup in a transparent manner.

5.1. Introduction

Ensuring sustainable supply of energy is one of the major challenges of the 21st century. The need for a renewable energy supply is increasingly becoming more urgent as conventional sources are blamed for the increasing levels of atmospheric greenhouse gases, global warming, and climate change. Moreover, reserves of fossil fuels are finite, and threatened by depletion (Shafiee and Topal, 2009). Also, fossil fuels reserves are not uniformly distributed over the world, therefore compromising the energy security of countries without the resource. However, developing countries have more diverse concerns including lack of access to adequate clean energy, extensive deforestation due to fuelwood harvesting and expansion of agricultural land. The end results are impacts such as soil erosion, loss of biodiversity and reduced availability and access to fuelwood resources by the population. With reduced accessibility to fuelwood, household fall down the energy ladder; thus, resorting to low quality energy sources such as agricultural residues and dried cattle manure, which have adverse impacts on the health of users due to increased indoor air pollution (Holdren et al., 2000).

Nevertheless, biomass combustion in inefficient devices remains the dominant household energy in most SSA countries. In Uganda, for example, over 90% of energy needs is provided by biomass, mainly in form of firewood, charcoal and agricultural residues

(Okello et al., 2013b). Despite the high potential of renewable energy resources in the country, it is estimated that only 5% of the population has access to electricity (Kaijuka, 2007). Currently, the country is experiencing high increase in demand for biomass energy, estimated at 3% and 6% for firewood and charcoal per annum, respectively (Kanabahita, 2001). The increasing demand coupled with expansion of agricultural land is leading to deforestation and consequently fuelwood deficit in many parts of the country (Drigo, 2005). To ensure sustainability of energy supply, the country developed the Renewable Energy Policy (MEMD, 2007) with the aim of increasing use of modern energy technologies, that are cleaner and more sustainable than existing practices. Under the policy, the use of improved stoves with higher efficiency is being promoted. The policy also aims at increasing the use of domestic biogas systems for household cooking and lighting. Consequently, several agencies are now promoting improved bioenergy technologies in the country. Examples of technologies promoted include improved biomass stoves, domestic biogas systems, biomass briquettes, and plant oil based systems. However the level of adoption of improved bioenergy technologies in Uganda remains low, with over 70% of the population using inefficient combustion devices (Okello et al., 2013b).

Generally, efforts to introduce improved renewable energy technologies in many communities are faced by multiple challenges including low adoption rates (Mobarak et al., 2012). In some cases, there are direct public opposition; a phenomenon commonly referred to as not in my backyard (NIMBY) effect (Ribeiro et al., 2011). This is probably due to public concerns such as competition with food production, change in land use and aesthetics. In some cases, renewable energy technologies are less economically competitive than fossil fuels or even against cultural norms and believe of the target population. For the case of Uganda, specific reasons for slow rates of adoption of improved bioenergy technologies are not clearly known.

Involving stakeholders is critical in understanding barriers to dissemination of bioenergy technologies and is recognised as key to successful implementation of the projects. Suitable tools are required to ensure successful consultation of stakeholders in the bioenergy decision making process. So far, several tools are available for the purpose, but one of the most popular is the analysis of strength, weaknesses, opportunities and threats (SWOT). The method has been widely used for participatory decision making; for example, Liu et al., (2011) used it to evaluate the social, economic and environmental impacts of bioenergy production on marginal land. Also, Lee et al., (2009) employed SWOT analysis to analyse and develop strategies for the development of Korean energy sector. A similar study using SWOT analysis was conducted in China for planning the strategic development of the Shale gas industry (Xingang et al., 2013). However, the main weakness of the SWOT analysis is that the results are not quantified and therefore difficult to attach levels of importance to individual SWOT factors identified.

Consequently, Kurtilla et al., (2000) developed a method that incorporates results of SWOT analysis in the analytical hierarchy process (AHP). The method, commonly abbreviated as SWOT-AHP or A'WOT has been widely used in forest policy decision analyses, examples include studies by Stainback et al., (2012), Masozera et al., (2006), and Dwivedi and Alavalapati, (2009). Other examples of the application of the method include studies in the field of safety and environment (Eslamipoor and Sepehriar, 2013), agriculture (Shrestha et al., 2004), and water resource management (Gallego-Ayala and Juízo, 2011). Ramirez et al., (Ramirez et al., 2012) conducted one of the first studies applying SWOT-AHP method to bioenergy technologies in developing countries to assess stakeholders' perception about non-traditional cook stoves in Honduras. However, all these studies are limited to the quantification of SWOT factors for a single scheme of intervention. Use of SWOT-AHP method as a tool for comparative analysis of strategic alternatives is generally limited in literature; an example was proposed by Pesonen et al., (2001).

Against this background, the objectives of the study were, to: 1) improve the capability of the SWOT-AHP methodology as a tool for participatory appraisal of alternative bioenergy technologies, and 2) illustrate the use of the proposed methodology with an application example. The present study gives a detailed description of the SWOT-AHP methodology and its proposed extension with desirability functions (Derringer G, 1980). An application example for participatory appraisal of four different bioenergy technologies in Uganda is also given.

5.2. Methodology

The proposed methodology incorporates desirability function (Karande et al., 2012) into the SWOT-AHP method, followed by synthesis of results using weighted summation method (Sudhakaran et al., 2013). In the SWOT analysis phase, strengths, weaknesses, opportunities and threats of the technology are analysed (Koo and Koo, 2007). The AHP methodology, developed by Saaty in the 1970s, can then be used to convert SWOT factors into quantifiable indicators, (Kurttila et al., 2000). Desirability functions (Karande et al., 2012) are then used to transform the weights of the SWOT group factors into measures of suitability of each technology. In the last step, ranks of technologies can then be subjected to sensitivity analysis (Geneletti, 2005) so as to evaluate their robustness to changes in weights of criteria. The flow chart of proposed method illustrated in Figure 5.1, and detailed explanation is given in the following sections.

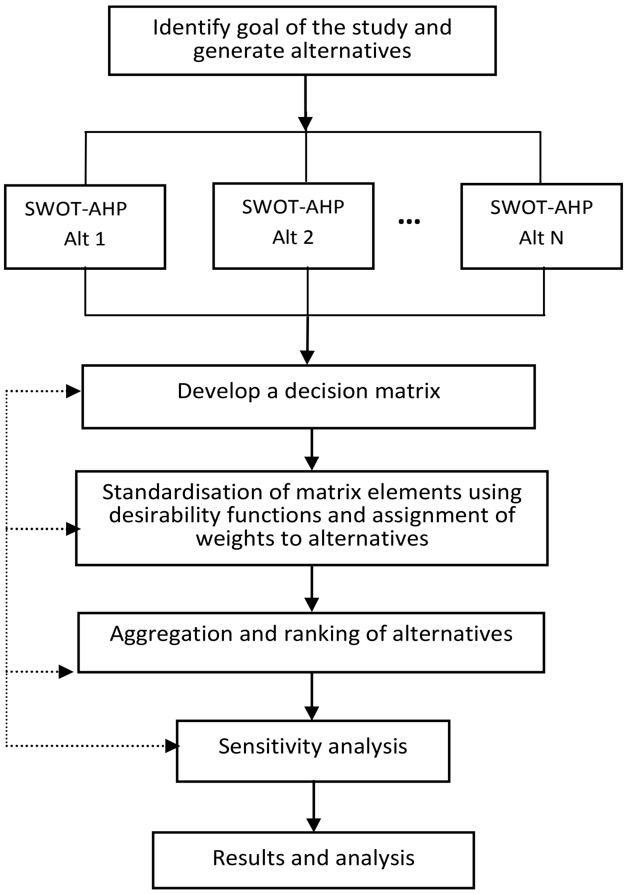

Figure 5.1. Flow chart of the proposed methodology. Note: doted lines show feedback between the stages). *Alt 1, Alt 2, …, Alt N,* represents the technologies under appraisal.

5.2.1 Incorporating SWOT in hierarchical decision model

The first step is to perform SWOT analysis of all the alternative bioenergy systems and incorporate the results in the hierarchical decision model (HDM) (van Blommestein and Daim, 2013), illustrated by Figure 5.2. At the top of the hierarchy is the decision goal. The criteria used in the decision model are the SWOT groups (Wang et al., 2009) of the respective energy systems. The more explicit SWOT factors are used as the sub-criteria in the model. At the bottom of the hierarchy are the alternative bioenergy technologies to be prioritised.

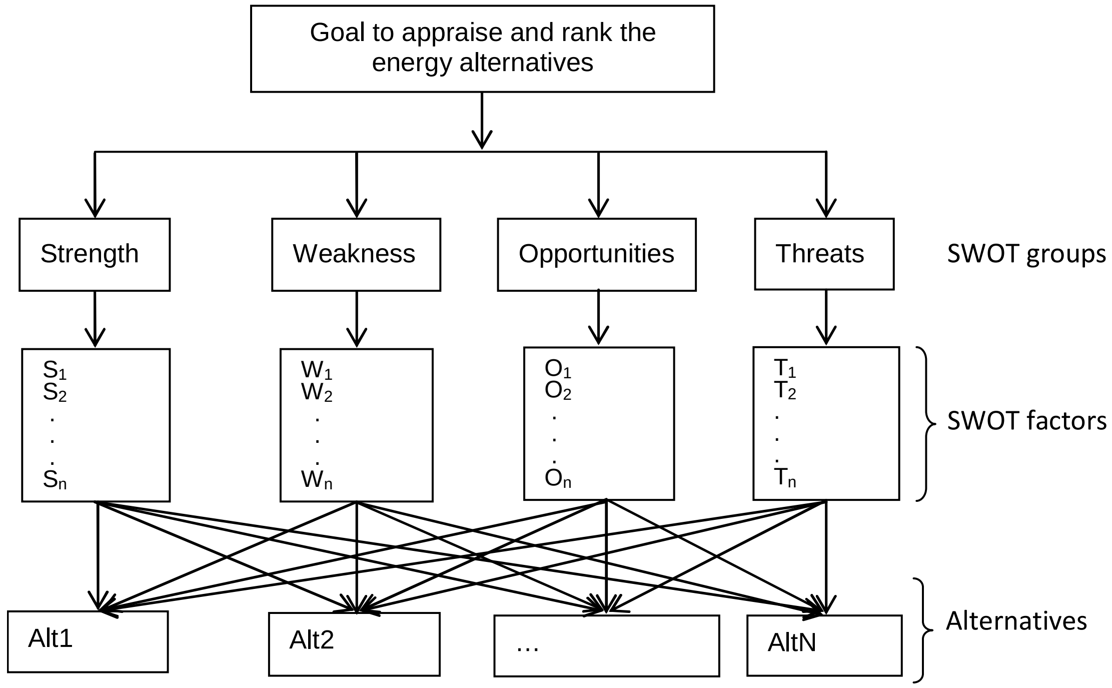

Figure 5.2. Hierarchical decision model. S_1, S_2, …, S_n; W_1, W_2, …, W_n; O_1, O_2, …, O_n and T_1, T_2, …, Tn represents strengths, weaknesses, opportunities and threats of each technology Alt1, Alt2, …, AltN, respectively.

5.2.2 Quantifying SWOT factors using AHP

In the second step, the SWOT factors (or sub-criteria) and SWOT groups (or criteria) are prioritised using pairwise comparison method (Wang et al., 2009). First, pairwise comparison of SWOT factors is done, followed by that of SWOT groups using a suitable scale, usually ranging from one to nine (Scott et al., 2012). Results of the pairwise comparison exercises are transformed into positive pairwise comparison matrices *A*, illustrated by Equation 5.1;

$$A = \begin{bmatrix} 1 & c_1/c_2 & \cdots & c_1/c_n \\ c_2/c_1 & 1 & \cdots & c_2/c_n \\ \vdots & \vdots & \ddots & \vdots \\ c_n/c_1 & c_n/c_2 & \cdots & 1 \end{bmatrix}, \tag{5.1}$$

where, c_i are the relative importance of SWOT factors or SWOT groups obtained from pairwise comparison. Values of c_i equal to one denotes equal importance between a given pair of factors or groups while nine indicates that one factor is absolutely more important than the other (Chang and Huang, 2006). Then, matrix A is normalised by dividing each element of a columns by the sum of the column elements, to generate Equation 5.2;

$$B = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix}, \tag{5.2}$$

where, B is the normalised pairwise comparison matrix. The weighted matrix, W, is then generated from the mean of each row of matrix B, as illustrated by Equation 5.3.

$$W = \frac{\sum_{j=1}^{n} x_{ij}}{n} = \begin{bmatrix} w_{11} \\ w_{12} \\ \vdots \\ w_{1n} \end{bmatrix}, \tag{5.3}$$

where, w_{ij} are the overall weights or scores of SWOT groups or factors of a given alternative. The result is then checked through consistency test by evaluating the value of consistency ratio, calculated using Equation 5.4.

$$CR = CI/RI \tag{5.4}$$

where, CR is consistency ratio, CI is consistency index given by Equation 5.5, RI is random index given in Table 5.1 (Scott et al., 2012).

$$CI = \frac{\lambda_{\max} - n}{n-1}, \tag{5.5}$$

where, CI, is the consistency index, $\lambda_{\max}$ is the largest Eigenvalue of matrix A, n is the number of SWOT groups or factors. It is a general rule that if the consistency ratio is greater than 0.1, then the results of the pairwise comparison is inconsistent, and therefore cannot be accepted (Benítez et al., 2011). Actions described in Sections 5.2.1 and 5.2.2 is repeated for each of the alternative under consideration.

Table 5.1. Values of random index (*RI*) (van Blommestein and Daim, 2013)

Matrix dimension (*n*)	Random index *RI*(*n*)
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45

5.2.3 Ranking of technologies

Ranking of the technologies is achieved by minimising the weaknesses and threats, and maximising strengths and opportunities. To achieve this, a decision matrix (Karande et al., 2012) is developed from the weights of SWOT groups, as illustrated in Table 5.2. Elements of the decision matrix are then transformed into a measure of suitability ranging from zero to one using desirability functions (Karande et al., 2012). A desirability value of one implies that the SWOT group factor is optimal, while a value of zero means the attribute is totally undesirable. Transformation of beneficial criteria, in this case strengths and opportunities, is done using Equation 5.6, while for non-beneficial criteria i.e., weaknesses and threats are using Equation 5.7.

$$d_i = \begin{cases} 0 & if \ w_{ij} \le w_{\min j} \\ \left(\dfrac{w_{ij} - w_{\min j}}{w_{\max j} - w_{\min j}} \right)^{\delta} & if \ w_{\min j} \le w_{ij} \le w_{\max j} \\ 1 & if \ w_{ij} \ge w_{\max j} \end{cases} \tag{5.6}$$

$$d_i = \begin{cases} 1 & if \ w_{ij} \le w_{\min j} \\ \left(\dfrac{w_{ij} - w_{\max j}}{w_{\min j} - w_{\max j}} \right)^{\delta} & if \ w_{\min j} \le w_{ij} \le w_{\max j} \\ 0 & if \ w_{ij} \ge w_{\max j} \end{cases} \tag{5.7}$$

In Equations 5.6 and 5.7, d_i are the individual desirability of SWOT group weights of a given alternative i; $w_{\min j}$ and $w_{\max j}$ are the maximum and minimum values of a given set of SWOT groups weights, respectively; derived using from Equation 5.3 and summarised in Table 5.2, and w_{ij} are SWOT group weights between $w_{\min j}$ and $w_{\max j}$. The parameter δ is a constant that determines the shape of the desirability function. When the value of δ is equal to 1, the function varies linearly between 0 and 1, in the case where δ is greater than 1, the shape is concave, while values of δ less than 1 results in a convex function.

Table 5.2. MCA decision matrix diagram

Criteria	Alternative technologies			
	A_1	A_2	…	A_n
C_1	w_{11}	w_{12}		w_{1n}
C_2	w_{21}	…	…	w_{2n}
…	…	…	…	…
C_n	w_{n1}	w_{n2}	…	w_{nn}

C_i are criteria, in this case SWOT groups
A_i are technologies to be ranked
w_{ij} are weights assigned to each SWOT group (see Section 5.2)

The overall desirability of a given alternative can then be calculated using the weighted summation method (Sudhakaran et al., 2013) according to Equation 5.8.

$$D_i = \sum_{i=1}^{n} \omega_i d_i \ , \qquad (5.8)$$

where, D_i is desirability of a given alternative bioenergy technology, ω_i are the weights assigned to SWOT groups i. The technologies can then be ranked basing on their overall desirability, and those with higher desirability values are the preferred options.

5.2.4 Sensitivity analysis

The last step is to carry out sensitivity analysis to determine the stability of the ranks of alternative bioenergy systems subject to changes in weights of SWOT group factors. During this process, point data is modified to observe their effects on the ranks of technologies, therefore enabling generation of scenarios (Geneletti, 2010).

5.3. Application of the methodology

5.3.1 Description of the study area

The study was carried out in Gulu municipality, located about 330 km by road, to the north of Ugandan capital, Kampala (Figure 5.3). The municipality is the second largest urban settlement in Uganda with an estimated population of 150,000 inhabitants (Mukwaya et al., 2011). Majority of households rely on charcoal and firewood as the main sources of domestic energy. However, the biomass resources in the area is being extracted faster than the rate of replenishment (Zanchi et al., 2013). A study Drigo (Drigo, 2005), indicated that the municipality is in net deficit of fuel wood resources. Recent efforts by the government and development partners led to increased use of energy saving stoves. Bioenergy technologies such as biomass briquetting, biogas and gasification are still new to the area and not widely.

Figure 5.3. Map of Uganda showing the location of study area, in circle (Based on UN map, Source: UN Cartographic section (2014))

5.4 Technologies considered in the study

Literature survey and field visits were carried out to identify possible bioenergy technologies that could be developed for use in the study area. Emphasis was placed on identifying technologies, which have been successfully employed in the country but not widely adopted. Where possible, samples of the technologies were acquired for demonstration during stakeholder workshop, otherwise, photographs were taken. The following is a brief description of technologies that were identified and considered for this study. More detailed explanation of these technologies is available in Okello et al., (Okello et al., 2013b).

5.4.1 Biogas system

Biogas technology was introduced in Uganda in the 1950s, and is one of the priority bioenergy technologies for cooking being promoted in the country (Sengendo et al., 2010). As per the renewable energy policy, Uganda has set a target of installing 100,000 domestic biogas digester by the year 2017 (MEMD, 2007). Estimates by MEMD (2007) indicates that the Uganda has a potential of 250,000 units of domestic digesters. Currently, the several governments and development partners are promoting the technology in developing countries, for example the SNV programme (Ghimire, 2013).

The model of the domestic biogas system is based on zero grazing cattle, which supplies manure used as substrate for biogas production. Digesters may be of fixed-dome, floating-dome or tubular designs (Nzila et al., 2012; Okello et al., 2013b). The fixed dome design is more popular in the country and was considered for this study. It is built of masonry and concrete and vary in volume from 8 m^3 to 16 m^3 (Walekhwa et al., 2009). Digestion chamber is airtight, therefore enabling anaerobic decomposition of the manure to produce biogas.

The system modelled in this study involves grass cultivation to ensure reliable supply of feeds to cattle, which are kept under a zero-grazing system. An acre of pasture is provided for each cattle; normally a household requires two or three heads of cattle to generate sufficient manure for biogas production. The bio-digester is constructed, underground and substrate is mixed with water and fed in the digester on daily basis. Simple burners are provided for combustion of the biogas, which is conveyed through pipes from the digester to the house.

Cooking with biogas provides advantages including improved efficiency and reduced indoor air pollution compared to traditional methods. Biogas production can also be integrated with food production and cattle products can improve food security and income of households. Slurry is known to be a very good organic fertilizer. However, the level of adoption is still low therefore requiring more understanding for the criteria of their sustainability.

5.4.2 Briquetting system

Biomass briquetting is the conversion of loose biomass material into a high density product by subjecting the material under pressure, with or without a binder (Mwampamba et al., 2013). The briquetting process involves material collection, drying, commutation and densification, using various types of presses (Samson et al., 2005). The resulting product is called briquette and is easier to handle and has better combustion properties than the original biomass material. Agricultural and forest residues could be used as raw material for briquetting (Okello et al., 2013a; Raman et al., 2013). Being an agro-based economy, Uganda produces large quantities of agricultural and forest residues. Recent estimates by Okello et al., (2013a), indicates that the gross energy potential of agricultural residues in Uganda amounts to about 260 PJ per year. Usually, the residues are burnt in the crop plantation during land preparation for planting, thus posing undesirable environmental problems.

The modelled briquetting system involves collection of maize residues, densifying it to briquettes, and using the briquettes in top-lit updraft (TLUD) gasifier stoves for cooking. Gasifier stoves were considered for the study because they are known to be more efficient than traditional stoves (Raman et al., 2013). The supply chained studied is based on maize residues, which is collected, sun dried, and commutated using a hammer mill to suitable size for briquetting. Briquetting is then carried out using piston press, powered by electrical energy.

Briquettes are known to have better handling, storage, transportation and combustion properties than the original raw material (Samson et al., 2005). The combustion appliance is a natural convection gasifier stove, and was selected because it is known to have higher efficiency and reduced particulate matter emission of 90% compared to the three stone traditional stove (MacCarty et al., 2010).

5.4.3 Charcoal systems

Charcoal is the most widely used energy source by urban population in Uganda and many other countries in sub-Saharan Africa. Charcoal production in Uganda is majorly informal (Sankhayan and Hofstad, 2000), based on harvesting and carbonising wood lots from natural forests. Trees are harvested using simple tools, such as axe and chain saws and tacked and covered with soil to form the traditional earth-mound kilns (Knöpfle, 2004). Wood used for the production is from natural forest, mainly found on privately owned land. The efficiency of the carbonisation process is less than 15%, and combustion takes place in charcoal stoves with efficiencies of about 10% (Knöpfle, 2004; Okello et al., 2013b). Charcoal production is a major employer and is blamed for the high deforestation rates in Uganda. Due to diminishing forest reserves resulting from extensive deforestation, price of charcoal is currently increasing rapidly.

Charcoal production takes place in the forest close to where the trees have been harvested. Processed charcoal is then transported to urban centres, mainly using bicycles for short distances or trucks for long distance delivery. There is a wide range of stoves designs that can be used for cooking with the charcoal, some of which are traditional and others improved with higher efficiencies. Charcoal fuel is popular in urban areas of developing countries because of reduced emissions and higher energy density compared to firewood. Charcoal value chain is known to be a major employer in Uganda (Sankhayan and Hofstad, 2000). However, presently, there are concerns about its impacts on the environments due to deforestation and loss of biodiversity.

5.4.4 Jatropha system

Under this system, a plantation of Jatropha (Jatropha curcas) is established by households. Jatropha fruits are harvested and manually de-hulled and sun-dried. Oil extraction is carried out using expellers, such as the "Sundhara" oil expellers, which are designed for a variety of oil seeds for use under rural conditions (Grimsby et al., 2012). Impurities in oil are allowed to settle before being decanted using gravitational method through a piece of cotton cloth. The oil is poisonous and thus not edible but can be filtered and used in crude form as cooking fuel in plant oil stove such as the Protos (Gaul, 2013; Kratzeisen and Müller, 2009). The stoves have better thermal efficiency and lower specific fuel consumption compared to the traditional stoves (Huboyo et al., 2013).

Jatropha is popular as a bioenergy crop because of its ability to reduce soil erosion and grow on marginal land with limited input of water and fertilizers. Jatropha plant has medicinal properties and is also known to be suitable for intercropping in agro-forestry system (Achten et al., 2008). The crude oil can also be used in Lister Petter® engines to produce mechanical power. This model is used in some parts of Africa to power multifunctional platform to provide mechanical and electrical power in rural areas (Nygaard, 2010). Alternatively the oil can be used for soap making soap, or upgraded to biodiesel through esterification and transesterification, therefore diversifying rural economy (Eckart and Henshaw, 2012). However, these advanced uses were excluded from the current scope of the study.

5.5 Data collection and analysis

5.5.1 Selection and composition of stakeholder panel

Data used in this study was collected during a one-day multi-stakeholder workshop held at Gulu University in February 2013. The workshop was attended by 28 participants from various interest groups. Participants were purposely selected (Stidham and Simon-Brown, 2011) to represent a broad spectrum of stakeholders of the bioenergy sector in the municipality. To ensure representativeness of the various interest groups, stakeholders were categorised into government, non-governmental organisation (NGOs), academic and research institutions, and private individuals and businesses using biomass for cooking. At least two participants from each stakeholder group participated in the workshop. The NGOs that participated are involved in promoting improved biomass stoves and biogas technologies in Gulu district. The researchers that participated in the workshop were from different departments of Gulu University, also located in the municipality.

5.5.2 Implementation of the workshop

The workshop was organised in three main sessions. During the first session, participants were introduced to the topic of bioenergy technologies, and the need for improved bioenergy technologies was explained. Different bioenergy technologies currently being promoted in country were explained to participants including challenges facing their dissemination and use. This was followed by a detailed explanation of the four bioenergy technologies to be ranked in this study. The process was made as participatory as possible so that participants could freely share their knowledge and experiences with the technologies. During the third session, participants were divided into four groups, and each tasked with development of SWOT factors for one of the technologies. Results of SWOT analysis developed by individual groups were presented to the general stakeholder's forum and discussed and a final list of SWOT factors agreed upon. Finally, the SWOT factors were typed in a specially designed spreadsheet format for pairwise comparison. These were printed and given to each participant to carry out pairwise comparison.

5.5.3 Analysis of results

Results of SWOT analysis were processed following the AHP procedure as described in Section 5.2. A spreadsheet programme was developed in Microsoft Excel® and used for pairwise comparison of the factors. The spreadsheet was also used to test for consistency of the pairwise comparison. Results were aggregated using geometric mean as recommended by Forman and Peniwati (1998). Ranking of technologies and sensitivity analysis were carried out using the MCA software called DEFINITE (2013). It was assumed that the SWOT factors had equal weights of 0.25. The sensitivity analysis phase was used to evaluate the effect of varying the weights on the ranks of the technologies. A numerical example of calculation steps used for ranking the technologies is given in Appendix A.

5.6. Results and discussions

5.6.1 Results of SWOT-AHP phase

Results of the SWOT-AHP phase is illustrated in Figure 5.4, and details of individual scores of the SWOT groups and factors are given in Appendix A, Table A3. The graphs show that biogas systems had opportunities ranked highest at 0.390, mainly due to increasing demand for the systems and its ability to provide decentralised energy services to individual households (Figure 5.4 (a)). Inadequacy of skilled personnel, lack of awareness about the technology and high investment costs were identified as the most detrimental factors to the adaption of biogas technology. Results of the briquette systems are given in Figure 5.4 (b), with its strengths scoring highest at 0.397. The most important strengths of briquettes identified were reduction in deforestation, cleanness and ease of handling. However, high investment costs and lack of skilled personnel were identified as most unfavourable factors to the technology. For charcoal systems, threats scored highest at 0.485 as shown in Figure 5.4 (c). This is mainly attributed to deforestation and land use change caused by charcoal production from natural forests. Meanwhile, opportunities of Jatropha system was greater than that of other SWOT group factors with a score of 0.481 (Figure 5.4 (d)), mainly due to job creation, opportunities for research and development of products to diversity rural economy and the favourable climate and soils. The poisonous nature of Jatropha and competition with other fuels were the most detrimental factors identified.

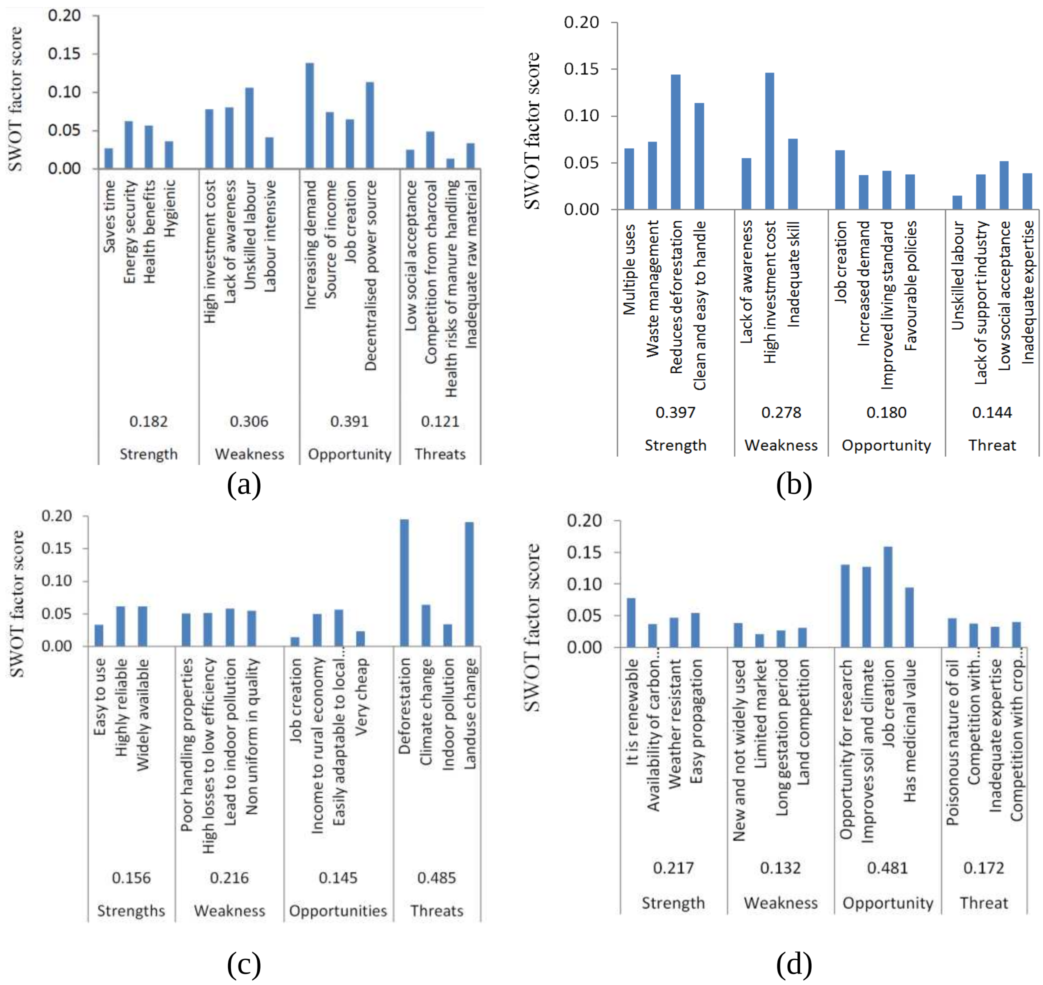

Figure 5.4. Stakeholder rating of SWOT factors and groups; (a) biogas, (b) briquettes, (c) charcoal, and (d) jatropha. (Only data that fulfilled consistency threshold were included in the results)

Results of the SWOT-AHP phase presented here demonstrates the ability of the methodology to identify issues that stakeholders consider as critical for selecting bioenergy technologies. Some of the issues identified by the stakeholders are in agreement with available literature, for example, Mwampamba et al., (2013) observed that briquetting has environmental benefits such as reduced deforestation, and offers opportunity for carbon credit. Threats of deforestation due to charcoal production (Chidumayo and Gumbo, 2013), and the environmental and health benefits of biogas (Bond and Templeton, 2011) are well documented in literature. High investment cost was identified as major challenges to the adoption of biogas (Bond and Templeton, 2011) and briquetting (Mwampamba et al., 2013) technologies in developing countries. Usually, success of biogas and briquette programmes in developing countries are attributed to substantial support from government and aid agencies (Chidumayo and Gumbo, 2013). On the other hand, the ability of Jatropha to grow on marginal land is seen as one of its main advantages and stakeholders rated this highly. The views expressed by the stakeholders were therefore in agreement with pertinent issues concerning the bioenergy technologies studied.

5.6.2 Ranks of technologies

The ranks of the four bioenergy technologies studied are given in Figure 5.5. Jatropha was ranked as the best technology with an overall desirability value of 0.78, while charcoal ranked lowest a desirability of 0.13. A numerical example illustrating how scores of energy systems presented in Figure 5.5 were calculated is given in Appendix A.

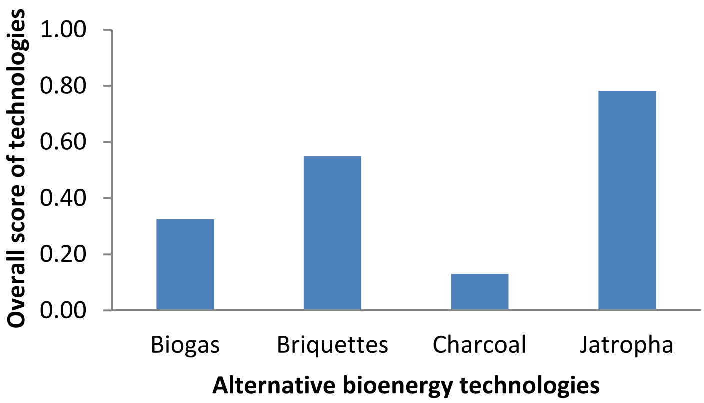

Figure 5.5. Scores of bioenergy technologies studied - higher scores are preferable**.**

Available literature indicates that Jatropha oil is a suitable fuel for small scale projects in sub-Saharan Africa, when used in multifunctional platforms (Eckart and Henshaw, 2012). It can be processed into biodiesel or used for making soap, therefore supporting diversification of rural enterprises (Dyer et al., 2012). However, there are debates about jatropha production; for example, it is reported to have a negative impact on carbon stock (Vang Rasmussen et al., 2012). Other challenges include low yield, limited know-how for feedstock conversion, high investment costs and inadequate private capacity to support the development of the sector (Ewing and Msangi, 2009).

5.6.3 Sensitivity analysis

The effect of varying factor weights on the ranking of the technologies was analysed through sensitivity analysis, and the results are shown in Figure 5.6. Biogas and briquettes were found to be highly sensitive to variation in the values of the weakness factors, with their scores dropping near to zero with high values of weaknesses. Charcoal is however more robust to variation of weakness values. Sensitivity analysis also indicates that rank reversal occurs between Jatropha and biogas systems, with biogas ranking highest when values of strengths were increased beyond 0.6. Therefore, both biogas and briquettes technologies would be acceptable by the community depending on management policies and incentives.

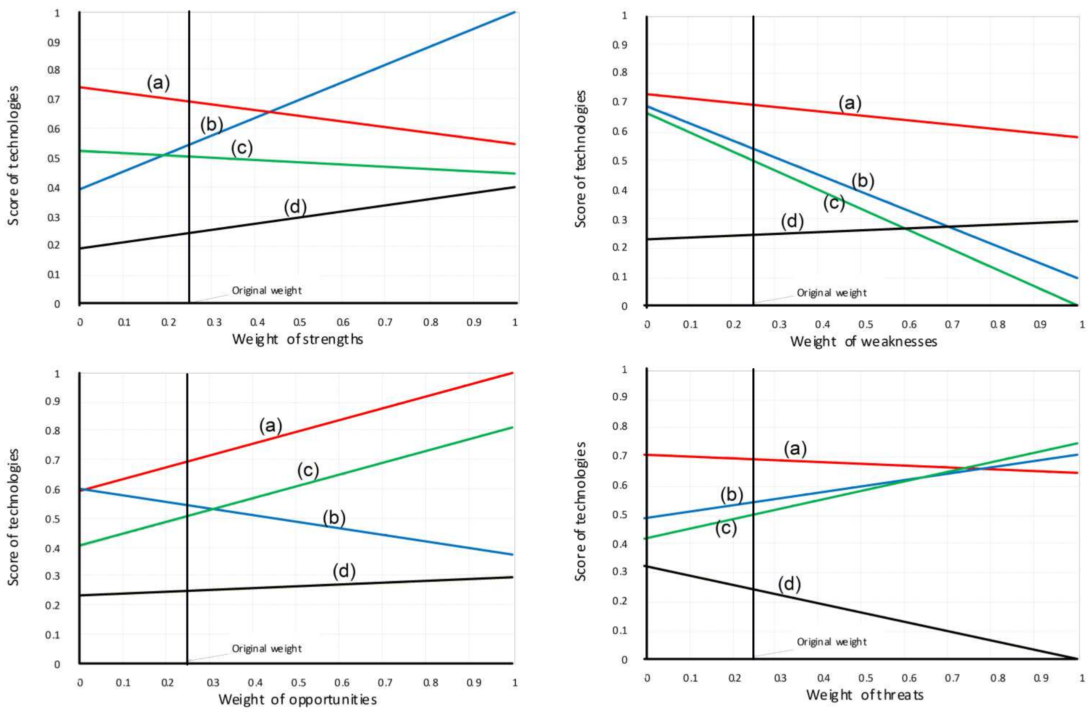

Figure 5.6. Sensitivity analysis plots (a) - Jatropha (b) - Briquettes (c) - Biogas (d) - Charcoal

5.6.4. Discussions on the methodology

In this study, we developed a method that incorporates desirability functions into the SWOT-AHP methodology for participatory appraisal of alternative bioenergy systems. The AHP methodology used is a very powerful multi-criteria analysis (MCA) tool with capabilities of allowing commensurability of both quantitative and qualitative variables. Use of pairwise comparison in AHP enhances the aptitude of the decision maker in the analysis of the alternatives therefore resulting in more rational decision. The method offers more flexibility over traditional approaches such as contingent evaluation, which requires that all variables are measured in dollar terms. The multi-criteria technique employed has capability of ranking multidimensional, conflicting and uncertain systems. Furthermore, participation of stakeholders in AHP studies is based on opinion leadership and representative democracy, therefore allowing for smaller number of samples than in statistical approaches (Masozera et al., 2006). The method is useful in environments where data for decision making is not readily available. It could help in identification of hidden interests, cultural constraints and other social values of the target community.

However, the methodology is based on some assumptions and has limitations that should be taken into consideration. First, during the SWOT analysis, there is likelihood that some factors proposed by participants may not be technically suitable for consideration. Therefore, the researcher has to ensure the appropriateness of the factors by ensuring legibility and avoiding redundancy (Munda, 2004). Secondly, the assumption of AHP methodology that the hierarchical factors are independent of each other may not necessarily be true, especially when complex systems are taken into consideration. This weakness could probably be reduced by integrating desirability functions in the SWOT-ANP (analytical hierarchy process) as suggested by Catron et al. (2013). Also, the SWOT methodology does not take uncertainties related to future development into consideration. As proposed by Kurttila et al., (2000) scenario modelling using dynamic SWOT analysis could be a possible solution to this limitation. As a rule, the number of SWOT factors for pairwise comparisons should be limited to 10; otherwise human cognition may not be capable of objectively carrying out pairwise comparison. In cases where this rule cannot be obeyed, grouping the factors under different categories is proposed as a remedy.

Much as the SWOT-AHP method is a very useful tool, it heavily relies on qualitative judgement of the SWOT factors. It does not incorporate measurable economic, social and environmental variables of sustainability. It is therefore recommended that it should be used to supplement other more rigorous methods such as financial cash flow or cost-benefit analysis (CBA) (O'Mahoney et al., 2013), life-cycle analysis (LCA) (Fazio and Monti, 2011) and life cycle costing (LCC) (Silalertruksa et al., 2012) Usually, these methods require considerable amount of data and time to implement. So, the proposed method may help in pre-screening of technologies that will most likely be accepted by the target community prior to more rigorous methods such as LCA, CBA and LCC. This is particularly important in developing countries where required data and logistics for their collection are often lacking. Pre-screening of technologies is advantageous since it helps to eliminate trivial options therefore enabling directing resources to a few promising alternatives. The method could also be used to identify stakeholders concerns about bioenergy technologies; thus, developing appropriate strategies for addressing them. Alternatively, the method could be used as a tool for reaching consensus in cases where there are conflicting interests among stakeholders. Generally, it could be used as a tool for soliciting stakeholder opinion during multi-criteria decision analysis of technologies, which considers social, economic and environmental aspects simultaneously (Nzila et al., 2012).

The application example presented is the first of its kind and could benefit from further trials. More rigorous data collection methods could be taken into consideration to evaluate the repeatability of the results. One could also study if there would be differences in the ranking of the technologies amongst different stakeholder groups. Furthermore, the possibility of incorporating other participatory techniques such as Delphi techniques could be taken into consideration to improve the overall rigour of the participatory process.

5.7. Conclusions

In this study, we proposed a methodology for participatory appraisal of technologies, and applied it in a case study to rank four bioenergy systems in Uganda. The methodology is intended to identify bioenergy technologies with a higher chance of public acceptance at the early stages of project development. The case study implemented showed that the tool is quite effective for identifying stakeholder preference of bioenergy technologies including the underlying reasons for their choices. The results of the study suggest that Jatropha could be accepted as a fuel for household energy in Uganda. Further, stakeholders regard charcoal as not sustainable mainly because of the threats it poses to the environment. Results suggest that suitable policies aimed at increasing affordability of bioenergy technologies could help increase their adoption rates in Uganda. Also, improving the critical mass of skilled personnel could play an important role to ensure increased dissemination of improved bioenergy technologies.

Chapter 6 – Sustainability criteria for bioenergy systems: perspectives of Ugandan stakeholders

Parts of this chapter was submitted to *Energy for Sustainable Development* as;

Okello, C., Pindozzi, S., Faugno, S., Boccia, L. Sustainability criteria for bioenergy systems: perspectives of Ugandan stakeholders. Energy for Sustainable Development (Submitted in November 2013).

Chapter 6 – Sustainability criteria for bioenergy systems: perspectives of Ugandan stakeholders

Summary

The need reduce greenhouse gas emissions, find replacement to fossil fuel resources, ensure energy autonomy and security has increased interest in biomass as a source of energy. Efforts are being made to ensure sustainability of bioenergy systems. This requires context specific criteria for assessing and monitoring progress towards sustainability. This study was therefore carried in Uganda with the objective to develop a shortlist of criteria for assessing sustainability of bioenergy systems used for domestic cooking and rank them according to their importance. Suitable indicators were identified and selected from available literature and ranked by a panel of multi-stakeholders. Pairwise comparison embedded in the analytical hierarchy process methodology was adopted for the purpose of ranking the criteria. In total, 21 criteria were selected on principles of relevance, practicality, independence and simplicity. Results show that the four most important criteria were of economic character, with investment and operational cost taking the first two positions, respectively. Next in importance were social criteria, which took the sixth to the tenth positions. Only one environmental criterion was among the top ten, that is, effects on human health, which took the fifth position. Further, results showed that environmental and technological criteria were ranked third and fourth in importance, respectively. This study suggests that critical attention should be given to social and economic aspects of the sustainability in order to achieve sustainable development of bioenergy for cooking in Uganda.

6.1 Introduction

Sustainability assessment requires that suitable criteria and indicators are selected for use as measures of sustainability. Criteria and indicator are useful tools for benchmarking, communication and decision making (Heijungs et al., 2010). Criteria are also used in assessment of certification schemes such as clean development mechanism and other biofuel sustainability standards. Progress towards achieving set of sustainability objectives are measured using indicators. Indicators measure the state of the environment, society and economy of a state or region, and can be integrated in some manner to an index, (Evans et al., 2009; Grimsby et al., 2013). They help to highlight concerns of experts and stakeholders in the bioenergy sector and are also useful for communicating the sustainability of the project or progress towards sustainable development (Kurka and Blackwood, 2013).

Consequently, there are currently several programmes initiated by national and international organisations that are developing policies and standards for sustainable biofuels and bioenergy along with associated sustainability criteria. For example, the European Commission developed the environmental criteria for biofuels and bio-liquids aimed at reducing greenhouse gas emission, conserving biodiversity and ensuring good environmental management practices in the Renewable Energy Directive (European Commission, 2009). Many individual EU member states are also developing national biofuel sustainability standards and criteria in line with the renewable energy directive, examples include the “Cramer Criteria” for sustainability of biomass and bioenergy developed in Netherlands (Cramer et al., 2006). Others are Renewable Transport Fuel Obligation in the UK, and Renewable Fuel Standards in the USA. Other initiatives include the Global Bioenergy Partnership, Roundtable on Sustainable Palm Oil production, Roundtable for Sustainable Soy Production and the Better Sugarcane Initiative (Scarlat and Dallemand, 2011; Van Dam and Junginger, 2011; van Dam et al., 2010). Development of sustainability criteria has also attracted interest of researchers, with particular emphasis to stakeholder opinion, examples include Buchholz et al., (2009), Kurka and Blackwood (2013), and van Dam and Junginger (2011).

As noted by van Dam et al., (2010), majority of the programmes on development of sustainability criteria of biofuels and bioenergy are generally concentrated in Europe and north America. Developing countries are generally lagging in criteria development, most especially those in the sub-Saharan Africa (SSA). This is notwithstanding the growing interest and investment in bioenergy projects in the region (Buchholz and Volk, 2012; Florin et al., 2013). Only few countries in the SSA have identified and incorporated sustainability criteria in their energy policies, some of which include Mozambique and South Africa (van Dam et al., 2010).

This study was therefore carried in Uganda with the objective to develop a shortlist of criteria for assessing sustainability of bioenergy systems used for cooking and rank them according to their importance. The ranking of criteria was carried out by a multi-stakeholder panel under four dimensions of sustainability; social, economic, environmental and technical.

6.1.1 An overview of the energy sector in Uganda and the study area

Uganda has one of the lowest access to electricity in Africa with only 5% of the households connected to the national (Kaijuka, 2007). The country has in recent past implemented reforms aimed at accelerating the development of the electricity sector. The reforms include the enactment of the Uganda Electricity Act in 1999, which provided for liberalisation of the sector, hence encouraging competition in electricity production, transmission and distribution. Also, Electricity Regulatory Authority was created to regulate the sector. However, even with these reforms, it is estimated that over 90% of the energy needs of Uganda is supplied by biomass fuels (Buchholz and Volk, 2012; Okello et al., 2013b). About 72% of Ugandan households use three-stone open fire and traditional biomass stoves for cooking. The stoves are with efficiencies in the range of only 10% (Kees and Feldmann, 2011; Okello et al., 2013b), and are associated with indoor air pollutants, with adverse impacts on the health of users.

Consequently, under the renewable energy policy for Uganda (MEMD, 2007), the country aims to increase the use of modern renewable energy from 4% in 2007 to 61% in 2017. Actions to achieve the goal include modernising bioenergy use by promoting production of commercial woodlots and energy crops. The policy set several targets to be achieved by 2017 including installing 100,000 units of domestic biogas systems, increasing use of energy efficient charcoal stoves from 20,000 to 2.5 million units, and wood stoves from 170,000 to 4 million units. Others targets include blending diesel fuel and gasoline with 20% biodiesel. Currently the government as well as non-governmental organisations are running several programmes aimed at achieving these targets (Ghimire, 2013; Kees and Feldmann, 2011; Okello et al., 2013b). The policy emphasises sustainable development of biomass energy systems, but currently there is no national guidelines and methodology for assessing sustainable biomass production and use.

This study was therefore carried out in Uganda to provide a benchmark for bioenergy sustainability assessment in the country. The present study was specifically carried out in the municipality of Gulu, in northern Uganda. The municipality, which is about 330 km north of Ugandan capital Kampala has a population of about 150,000 people, and is the second largest urban settlement in the country (Mukwaya et al., 2011). It was chosen for the study because according recent to studies by Drigo (2005), the municipality is in net deficit of fuel wood resources. Therefore, there is need to develop sustainable bioenergy systems for cooking in the municipality.

6.1.2 Technologies for which criteria were evaluated

The criteria were selected to suit sustainability assessment of domestic biogas system, Jatropha plant oil, and gasification of densified residues. The charcoal systems were also considered as a baseline scenario. Apart of charcoal, which is widely used in the municipality, the other three technologies are relatively new in Uganda, and not widely disseminated. A detailed description of each technology supply chain is given in Section 5.4 of this thesis.

6.2 Methodology

6.2.1 Overview

An overview of the steps followed for the selection and ranking the criteria for assessing sustainability of the bioenergy technologies is illustrated in Figure 6.1. First, a literature review was carried out to develop a preliminary list of criteria, which was then subjected to a filtering process. Filtering was based on conditions that suitable criteria exhibit relevance, practicality, independency and simplicity as defined in Table 6.1. Criteria that fulfilled all the four conditions concurrently were selected for further analysis and ranking by a multi-stakeholder panel according to their importance. Ranking for importance was conducted using pairwise comparison process of the analytical hierarchy process (AHP) methodology.

6.2.2 Identification of preliminary list of criteria

The preliminary list of criteria was developed through a review of relevant literature. Literature consulted include studies by Beccali et al., (2003), Buytaert et al., (2011), Kurka and Blackwood, (2013), van Blommestein and Daim, (2013), Wang et al., (2009), Perimenis et al., (2011), Nzila et al., (2012), and Phalan, (2009). The criteria were classified under social, economic, environmental and technical dimensions of sustainability.

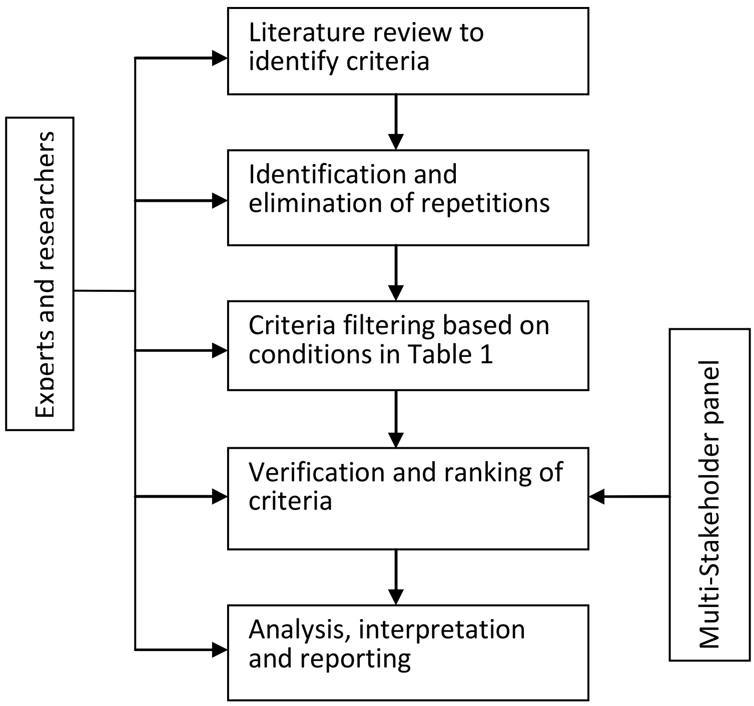

Figure 6.1. Chart showing workflow and roles experts and stakeholders

6.2.3 Filtering of criteria

According to the Bellagio Principles, (Hardi and Zdan, 1997) criteria should be limited in number. Consequently, to select the most relevant criteria from the preliminary list, a process of filtering was carried out. This was based on a set of conditions (Kurka and Blackwood, 2013; Neves and Leal, 2010; Van de Kerk and Manuel, 2008; Zhen and Routray, 2003) listed in Table 6.1. Criteria that simultaneously fulfilled all the conditions qualified for the next stage of analysis.

Table 6.1. Conditions for selecting sustainability criteria of bioenergy systems

Selection criteria	Brief description
Relevance	The criteria for sustainable bioenergy should be relevant to the alternatives under consideration.
Practicality	Data should be easily to obtain or measure in a resource effective manner.
Independency	Criteria should be independent enough, that is, they should not duplicate each other.
Simplicity	Criterion can be easily understood by all stakeholders.

6.2.4 Structuring the multi-stakeholders panel

In the selection of the multi-stakeholders panel, we adopted a broad definition of stakeholders by Gold (2011) as any identifiable individual or organisation that can affect the objectives or who may be affected by achievements of objectives of an entity. In this perspective, stakeholders were broadly classified as internal or external to the bioenergy supply chain. Internal stakeholders are individuals or organisations directly involved in the production and use of bioenergy, while external are those who may have any influence on supply the chain. A summary of the different categories of stakeholders groups identified is given in Table 6.2. To ensure comprehensiveness in selecting the multi-stakeholders panel to participate in the study, the maximum variation sampling (Stidham and Simon-Brown, 2011) was adopted. This was by ensuring that each of the stakeholder group given in Table 6.2 was represented in the panel. In total, 28 stakeholders from the different categories participated in the study.

Table 6.2. Classification of stakeholders in Ugandan bioenergy sector

Stakeholder	Role in bioenergy sector
Governmental organisations	Renewable energy policy development, approval of bioenergy projects, ensuring environmental and social sustainability of projects, provision of suitable investment climate, provision of incentives
Nongovernmental organisations and civil society organisations	Funding, research and development, social watchdogs – protects local communities and rights of marginalised, involves local communities, research and development, outreach
Academic and research institutions	Research and development, outreach and technology dissemination
Private sector businesses and associations	Production and market for feedstock, users of bioenergy technologies. Coordination of land holders and the private bioenergy sector, dissemination of ideas
Local community	Participation in plantation establishment and management, cultivation of feedstock, provision of land, production and market for feedstock, users of bioenergy technologies.

6.2.5 Ranking of criteria

The pairwise comparison method embedded in the analytical hierarchy process (AHP) methodology was employed to rank the sustainability criteria. The AHP (Saaty, 1980) methodology was developed by Saaty in the 1970s and has been widely used as a decision making tool for various applications (Tsita and Pilavachi, 2013; Uyan, 2013). The methodology is executed in four steps: first, the overall objective of the study is specified. Next, the problem is structured into a decision hierarchy consisting of the goal, criteria, sub-criteria and alternatives. In the third step weights are assigned to the criteria through pairwise comparison. This process starts with criteria at the lower level of the hierarchy, and progresses to those at the higher levels respect to the preceding steps. Lastly synthesis of the weights is carried out in order to rank the alternatives as described by Kablan (2004) and Saaty (2008). More details on the AHP methodology is given in Section 5.2.

The decision matrix for the problem was developed and given in Figure 6.2. Ranking of criteria was conducted by a panel of multi-stakeholders during a consultative workshop held at Gulu University in February 2013. The main objective of the workshop was to solicit the opinion of stakeholders on the importance of sustainability criteria for the bioenergy systems used for cooking in Uganda.

The workshop was structured into three sessions; first general background information on sustainability of energy systems was introduced to participants. This was followed by an elucidation session where the list of selected criteria were introduced and explained to participants by experts on social, economic, environmental and technical issues. At this stage, further filtering of the criteria was performed to come up with the final list. Finally, stakeholders were provided with forms for pairwise comparison of individual criteria along with a summary of their definition. Stakeholders weighted the importance of the criteria using pairwise comparison, by indicating which of a given pair of criteria was more important than the other and my how much. For the purpose of this study, the AHP method was performed up to third step, since the goal of the study was to assign importance to the criteria. Data of the pairwise comparison was analysed and individual scores were aggregated using geometric mean (Forman and Peniwati, 1998) to determine the aggregated score of the multi-stakeholder panel. The alternatives given in the hierarchical structure in Figure 6.2, were included in the hierarchy to ensure that the criteria were relevant to all of them (Kurka and Blackwood, 2013).

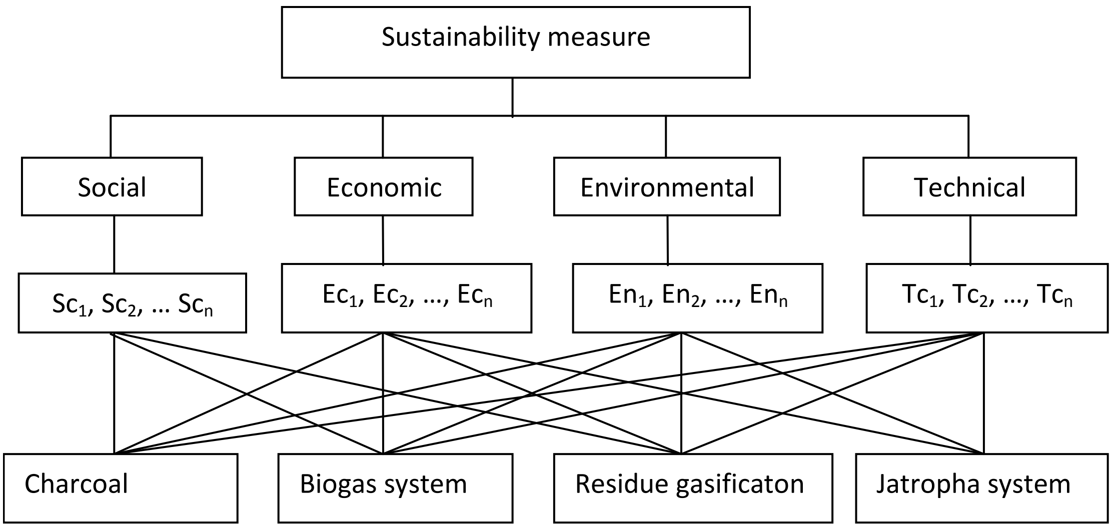

Figure 6.2. Decision matrix for ranking importance of sustainability criteria. Sc_i, Ec_i, En_i and Tc_i are social, economic, environmental technical criteria, respectively. Subscript $i = 1, 2, \dots, n$ are criteria number

6.3 Results

6.3.1 Preliminary list of criteria

The preliminary list of criteria identified from literature review is given in Table 6.3, totalling 65 in number. The criteria were classified under social, economic, environmental and technical dimensions of sustainability. The technical dimension of sustainability had the highest number of criteria, totalling 20, followed by economic at 16 and environmental and social dimensions at 15 and 14, respectively. Table 6.3 also shows the suitability of criteria based on their relevance, practicality, independence and simplicity. From the literature review, it was observed that some criteria were classified under more than one dimension of sustainability. For example, energy autonomy has featured as a social as well as an economic criteria, it was recorded as social criteria in this study.

Table 6.3. List of Criteria identified from literature with results of selection criteria

Dimension	Criteria	Relevance	Practicality	Independency	Simplicity
Social	Social acceptability	√	√	√	√
	Job creation	√	√	√	√
	Legislative requirements	√	√	√	√
	Social inclusion	√	√	√	√
	Market maturity	√	√	×	√
	Energy autonomy	√	×	√	√
	Protection of property rights (land tenure conflict)	×	×	√	√
	Protection of human safety and health	√	√	×	√
	Labour conditions and labour income	√	√	×	√
	Capacity building of local human resource	√	√	×	√
	Fair trade conditions	×	×	√	×
	Food security in context of bioenergy development	√	√	×	√
	Accessibility, affordability and disparity	√	√	×	√
	Social well-being	√	√	√	√
Economic	Investment cost	√	√	√	√
	Operation and maintenance cost	√	√	√	√
	Viability - Net present value (NPV)	√	√	√	√
	Payback period	√	√	×	√
	Equivalent annual cost	√	√	×	√
	Labour cost	√	√	×	√
	Energy price to end user	×	√	√	√
	Macroeconomic sustainability	√	×	√	×
	Risk minimisation	√	×	√	√
	Strength and diversification of local economy	√	×	√	√
	No blocking of other desirable developments	√	×	√	√
	Institutional capacity	√	×	√	×
	Service life	√	√	√	√
	Institutional well-being	×	×	√	×
	Utility incentives/rebate	√	×	√	√
	Savings per month	√	×	√	√
Environmental	Reduction of climate change effects	√	√	√	√
	Particles emission	×	×	×	×
	Land use change	√	√	√	√
	Loss of biodiversity	√	√	√	√
	Noise pollution	√	√	×	√
	Primary energy demand	√	×	×	√
	Soil degradation	√	√	√	√
	Resource depletion	√	√	×	√
	GHG emissions	√	√	×	√
	Water depletion and pollution	√	√	√	√
	Impact on human health	√	√	√	√
	Air quality due to non GHG emissions	√	√	×	√
	Ecological justice	√	×	×	×

Table 6.3 Continued …

Dimension	Criteria	Relevance	Practicality	Independency	Simplicity
Technical	Functionality	√	√	√	√
	Reliability	√	√	√	√
	Usability	√	√	√	√
	Technical efficiency	√	√	√	√
	Maintainability	√	√	√	√
	Exergy efficiency	√	√	×	×
	Portability	√	√	√	√
	Installed capacity	×	√	√	√
	Energy breeding ratio	√	√	×	×
	Energy payback	√	√	√	×
	Conversion ratio	√	√	×	×
	Complexity	√	√	×	√
	Development status	√	√	×	√
	Technical maturity	√	√	×	√
	Continuity and predictability	√	×	×	√
	Health and safety of energy system	√	√	×	√
	Energy balance	√	√	×	√
	Safety	√	√	×	√
	Effectiveness	√	×	×	√
	Upgradability	√	√	×	√
	Waste generation and management	√	×	×	√
	Natural resource efficiency	√	√	×	√

6.3.2 Summary and description of selected criteria

The final list of criteria for sustainability of the bioenergy systems is summarised in Table 6.4 along with a brief description of each. Six criteria were selected for the technical and environmental dimensions of sustainability, while social and economic dimensions had five and four criteria, respectively.

6.3.3 Ranks of sustainability dimensions

The social, economic, environmental and technical dimensions of sustainability were ranked by stakeholders using pairwise comparison according to the AHP methodology, and the result is given in Figure 6.3. The figure shows that the economic dimension of sustainability was ranked as most important with a score of 0.352. Since the total score of all the four dimensions add to one, the value 0.352 can be interpreted as economic criteria influence 35.2% of the sustainability considerations of bioenergy systems for cooking in the study area. More detailed presentation of the results of the importance of sustainability dimensions are given in second column of Table 6.5. It can be observed that the social dimension of sustainability was second in rank with an influence of 25.4%, while technical dimension had the lowest influence of 17.7%. Stakeholders therefore consider economic and social considerations as most important sustainability dimensions in their decision to select bioenergy systems for cooking.

Table 6.4. List of bioenergy sustainability criteria for Uganda and their description

Sustainability dimension	criteria	Description of criteria
Social	Acceptability	Harmony with cultural or traditional values and beliefs that may hinder the dissemination of the technology
	Job creation	Increase in direct or indirect employment due to the introduction of the technology
	Legislative requirements	Compatibility with the political, legislative and administrative requirements
	Social well-being	Impact on income, and food security, energy autonomy or any general welfare of the society
	Social inclusion	Possibility of use by a broad spectrum of the society irrespective of their social status such as gender, education level, disability etc.
Economic	Investment cost	The cost of introducing the new technology, including all cost required to implement the project
	Operation and maintenance cost	Sum of all fixed and variable costs required for operating the bioenergy equipment
	Financial viability	Possibility of being profitable as measured by net present value and payback period
	Service life	Period of time in years when the systems is still economically useful
Environmental	Reduction of climate change effects	Contribution of the technology towards reduction of climate change, through reduction of greenhouse gas emissions
	Loss of biodiversity	Loss of plant or animal species as a result of operation of the bioenergy system
	Soil degradation	Loss in quality or quantity of soil due to erosion or pollution
	Impact on water resource	Reduced availability or quality of water resources
	Land use change	Conversion of existing use land resources to other activities undesirable activities of bioenergy production
	Impacts on human health	Injury or negative impacts on health of users
Technical	Functionality	The capability of bioenergy systems to provide functions, which meet stated and implied.
	Reliability	The capability of bioenergy systems to maintain its level of performance for a specified period of time
	Usability	The capability of bioenergy systems to be understood learned, used and attractive to the user.
	Energy efficiency	The capability of bioenergy systems to provide reasonable output, relative to the amount of resources input
	Maintainability	The capability of the systems to be modified. Modifications may include corrections, improvements or adaptations of the bioenergy systems to changes in the environment and in the requirements and functional specifications
	Portability	Easy flexibility to current conditions, easy to install, replicate and replace.

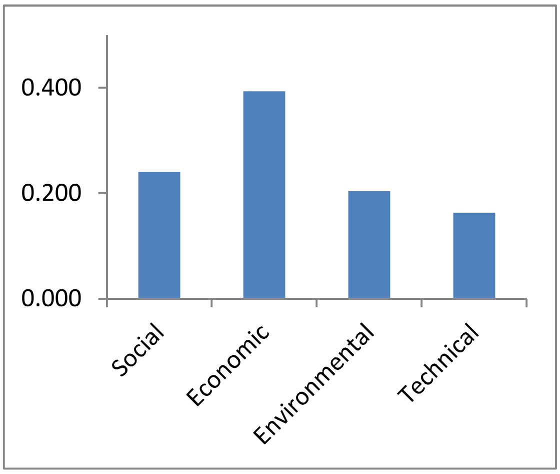

Figure 6.3. Ranks of sustainability dimension

6.3.4 Local importance of sustainability criteria

The importance of the social, economic, environmental and technical criteria of sustainability is given in Figure 6.4. Actual values of the local importance of each criterion are given in the fourth column of Table 6.5. Figure 6.4 (a) indicates that social well-being was most significant social criterion with local importance of 0.225. Meanwhile, Figure 6.4 (b) shows that capital and operating costs are the most important economic criteria for sustainability of bioenergy for cooking in this study. Capital cost was scored at 0.314, implying 31.4% of economic considerations for sustainability of the bioenergy systems is contributed by this criterion. This is followed by operation and maintenance cost with a contribution of 27.1%, while viability was the least important. For the case of environmental criteria, impact on human health had the highest importance with a local importance of 26.7%. Also, it can be observed from Figure 6.4(d) that efficiency was ranked as most significant amongst the technical criteria with a local importance of 21.3%.

Table 6.5. Results of importance ranking of criteria and dimension energy sustainability

Sustainability dimension	Importance [a]	Criteria	Local importance [b]	Global importance [c]
Social	0.254	Acceptability	0.206	0.052
		Job creation	0.192	0.049
		Legislations	0.183	0.047
		Social well-being	0.225	0.057
		Social inclusion	0.194	0.049
Economic	0.352	Capital cost	0.314	0.110
		Operating cost	0.271	0.095
		Service life	0.232	0.082
		Viability	0.183	0.064
Environmental	0.218	Climate change	0.188	0.041
		Loss of biodiversity	0.121	0.026
		Soil degradation	0.115	0.025
		Water degradation	0.166	0.036
		Land use change	0.143	0.031
		Human health effects	0.263	0.057
Technical	0.177	Functionality	0.158	0.028
		Reliability	0.192	0.034
		Usability	0.182	0.032
		Energy efficiency	0.213	0.038
		Maintainability	0.171	0.030
		Portability	0.084	0.015

[a] Scores derived from pairwise comparison of social, economic environmental and technical criteria;
[b] Scores derived from pairwise comparison of criteria under each dimension of sustainability,
[c] The product of elements of second and fourth column, with respect to each sustainability dimension

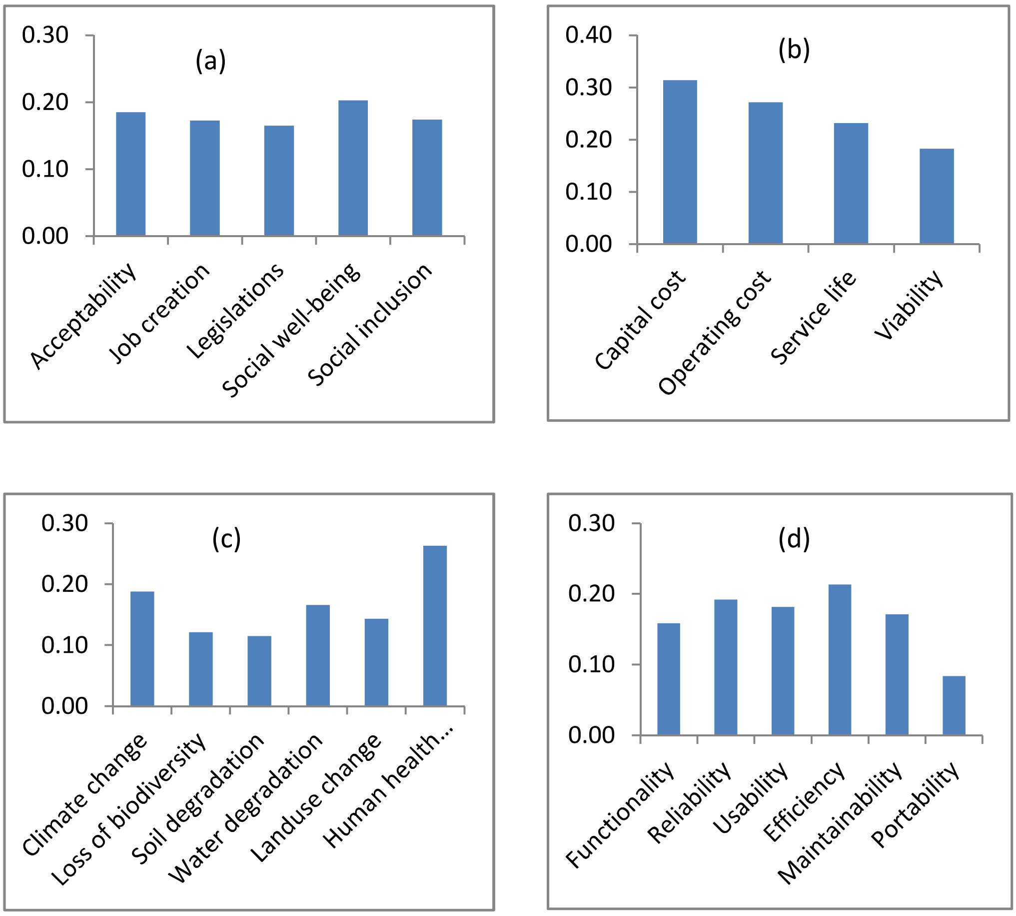

Figure 6.4. Ranks of criteria under each sustainability dimension: (a) social criteria, (b) economic criteria, (c) environmental criteria, and (d) technical criteria.

6.3.5 Global importance of criteria

The global importance of the 21 criteria of bioenergy sustainability was calculated, and results of this analysis are shown in the last column of Table 6.5. To facilitate interpretation, the relative importance was plotted on a graph in descending order as shown in Figure 6.5. The figure shows that economic criteria were generally ranked to be more important in comparison to the other dimensions of sustainability. Actually, the first four most important criteria were of economic dimension, with the capital and operating costs being the ranked as most important, with global scores of 0.110 and 0.095, respectively. This implies that capital and operating cost influences almost 20% of the overall sustainability considerations of bioenergy systems for cooking in the study area.

Figure 6.5 further shows that social criteria were ranked second in importance to the economic criteria, taking the seventh to the tenth positions. Apart from impact on human health, which took the sixth position, all the other environmental criteria were ranked from the eleventh position and above. Also, none of the technical criteria featured amongst the top eleven criteria in the ranking. The most important technological criterion, that is efficiency, took the twelfth position in the ranking. Stakeholders ranked the portability of a technology as the least overall in global importance.

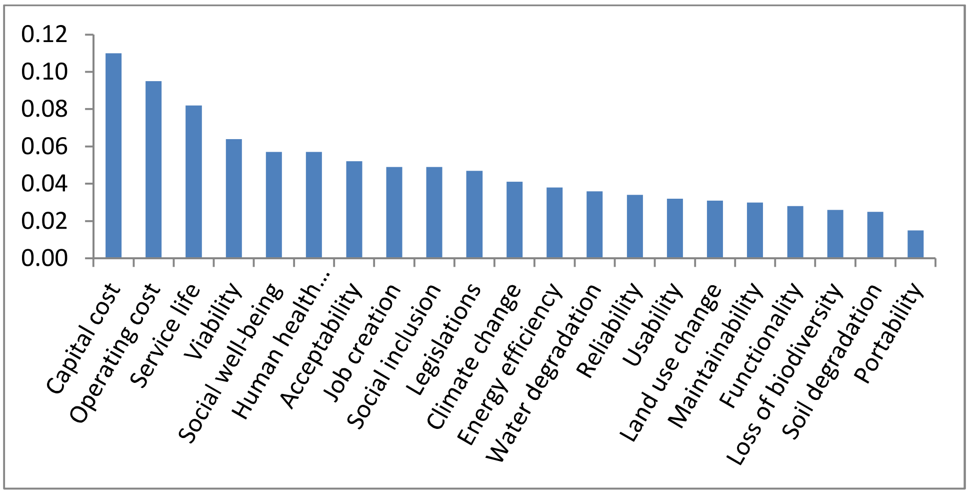

Figure 6.5. Global priority ranks of all sustainability criteria under.

6.4 Discussions

This study aimed at identifying and ranking criteria for sustainability for bioenergy systems cooking in Uganda. A total of 21 criteria were selected and opinion of a multi-stakeholder panel was solicited to determine the relative importance of criteria for assessing sustainability of four different bioenergy systems for cooking. In the study, criteria were categorised under economic, social environmental and technological dimensions of sustainability. The results showed that sustainability of the energy systems is depend on fulfilment of all the 21 sustainability criteria identified. Generally, economic and social criteria were given the highest importance in the ranking. This study is one of the first efforts aimed at identifying criteria for sustainable bioenergy systems for cooking in Uganda and provides useful information for future multi-criteria analysis (MCA) studies in the study area.

6.4.1 Economic criteria

The findings of this study indicate that economic dimension of bioenergy sustainability was given more weight than the social, environmental and technical. This finding is contradicts that by Buchholz et al., (2009), who reported that bioenergy experts from across the world raked environmental criteria as most important followed by social criteria, while economic criteria generally ranked lower on the list (Buchholz et al., 2009; Markevičius et al., 2010). This disparity is probably explained by the fact that of the 66 experts in the study by Buchholz et al., (2009), 46 of them were from Europe and America, where there is more knowledge and awareness about environmental issues. Better understanding and awareness of the experts on environmental concerns of bioenergy systems probably explains the high score reported by Buccholz et al., (2009).

Generally however, developing countries are constrained by financial resources for investment in more sustainable bioenergy technologies, and this probably justifies the high importance allocated to the economic criteria. The finding of this study is also in agreement with available literature, that have frequently reported that economic constraints as a major barrier to dissemination of improved bioenergy systems in developing countries. Actually, it is reported that in most cases, adoption of improved bioenergy technologies in many developing countries have been because of subsidies from the government and other development agencies (Bond and Templeton, 2011; Chidumayo and Gumbo, 2012; Mwampamba et al., 2013). This suggests that strategies aimed at providing subsidies, such as tax exemptions, and grants for the development of bioenergy supply chains, would facilitate sustainable development of bioenergy systems as recommended by Mangoyana (2009). However, it should be noted that most governments of developing countries are also resource constrained and access to credit facilities from financial institutions is usually limited. Therefore, more innovative approaches aimed at reducing investment and operation costs of the technologies could probably be worthwhile. This could be achieved through research and development of innovative energy systems for cooking.

6.4.2 Social criteria

Results of this study indicate that stakeholders scored social dimension of bioenergy sustainability second in importance to the economic criteria. Social well-being was given the highest importance under this category. Generally, introduction of bioenergy systems, especially large scale projects, are known to have both positive and negative impacts on the well-being of a society (Dale et al., 2013). Positive impacts may include increase in household health due to reduced indoor pollution or even new employment in the supply chain of the technology. However, certain negative aspects of the technology could result in negative impacts on the society, for example introduction of energy crops on a large scale may result in competition with food production, therefore negatively affecting the welfare and sustainability of the society. Concerns about food security is particularly important in developing countries where food production is still inadequate, and has been widely reported in literature (Dale et al., 2013; Phalan, 2009). These issues probably explain the high level of importance given to social well-being as criteria for sustainability.

Next in importance was social acceptance of bioenergy technology. Acceptance of a technology may be influenced by a number of factors including awareness of the technology, relative advantages, complexity, as well as perception (Mallett, 2007). As noted by Wüstenhagen et al., (2007), social acceptance can be conceptualised at three broad levels. First is socio-political level where technology acceptance should be aligned to existing policies, public and stakeholder interests. Next are the market and community acceptance which involve the actual adoption of the innovation. The last two categories are particularly critical in developing countries like Uganda, where it is usually the producer who is the final consumer of the bioenergy products and services. The high importance given to social acceptance suggests the need for transparency in the planning the bioenergy projects. This should aim at building trusts in the community about the information and overall intention of the project by giving opportunity to relevant stakeholders to participate throughout the decision making process.

6.4.3 Environmental criteria

Environmental dimension of bioenergy sustainability was rated third in importance in this study. Generally, bioenergy systems are credited for their ability to be carbon neutral when produced in a sustainable manner. Nevertheless, there several environmental problems that can arise from bioenergy projects, including emissions of greenhouse gases, direct impact on human health, land use change, loss of biodiversity and negative impacts on soil and water resources. Air pollution and acidification and other environmental challenges are also related to use of bioenergy. Of particular concern in this study was the impact on human health that was rated by stakeholders as the most important environmental criteria. Current bioenergy systems used in many developing countries are characterised by low efficiencies and excessive emissions of poisonous gases. The emissions of non greenhouse gasses such NOx, CO, SO_2 and particulates results in decline in air quality and are a major cause of indoor air pollution resulting in acute respiratory tract infection of users. Other health issues are related to workers safety in the supply chain of the bioenergy system.

Next in importance to human health was the climate change criterion, which comes as a results global warming caused by increased levels of greenhouse gases such as CO_2, CH_4 and S_2O in the atmosphere. In most cases, production of bioenergy results in a negative greenhouse balance. However, in certain cases, such as when carbon-rich vegetation is replaced by energy crops can result in a positive greenhouse balance. Also, use of nitrogen-based fertilizers to improve yields of energy crops could result in emissions of N_2O, which has 100 year global warming potential of 296 (Robertson and Grace, 2004). With this background, production of bioenergy crops on degraded land is could be advantageous as a means of reducing GHG emissions, and may result in negative GHG balance. The choice of the energy crop is also important, for example *Jatropha curcas* L. is known to grow well with minimum inputs of fertilizers and could therefore benefit from reduced N_2O emissions.

Impact on water resources was identified as the third most important environmental criteria of bioenergy sustainability. Bioenergy impacts on water resources may be in the form of reduced availability or quality of water. Care should therefore be taken especially when introducing crops such as of Eucalyptus, which are known to result in reduction in groundwater yields (Hanegraaf et al., 1998; Robinson et al., 2006). This is particularly important since most of the population in the study area depend on natural springs as source of domestic water. Water quality may also decline due to application of fertilizers to energy crops resulting in increased phosphorus and nitrogen concentration thus leading to eutrophication. Other concerns may include sedimentation due to increased runoff caused by land-use change to energy crops.

6.4.4 Technical criteria

Findings of this study indicate that the technical criteria were ranked lowest in importance amongst the four dimensions of sustainability. This is rather a surprise taking into consideration that many developing countries lack required skilled personnel to implement new bioenergy technologies. The efficiency of the bioenergy system was given the highest score as a criterion for sustainability of the bioenergy technologies under study. Generally, improvement of energy efficiency is expected to result in reduction in energy consumption and related benefit to the environment such as reduced deforestation. Consequently, many developing countries, including Uganda are now promoting use of improved stoves with higher efficiencies than the traditional types. However, it has been observed that sometimes these benefits are not necessarily obtained since increased savings may result in an overall increase in consumption, a phenomenon popularly known as rebound-effect. For example, Zein-Elabdin (1997), found that up to 41.7% of the designed fuel efficiency gains may be lost from improved stoves programme in Sudan. More detailed discussions on rebound effect and generally on Jevons Paradox can be found in Sorrell (2009). Therefore, it is important that the changes in bioenergy demand resulting from improved efficiency is critically assessed. Such information is generally lacking in many energy programmes in sub-Saharan Africa, and could be of interest in future studies.

6.4.5 Considerations for future work

Future work could involve developing and quantifying suitable indicators for all the criteria identified in this study. The environmental and economic indicators could be developed through the life cycle approaches such as life cycle costing and life cycle assessment in order to generate measurable indicators. However, it should be noted the analyses will most likely be faced with the challenge of lack of suitable data concerning bioenergy systems in the study area, as is the case in many developing countries. Further work could also involve developing appropriate methods for aggregation to derive sustainability indices that can be used to compare performance of alternative energy systems.

6.5 Conclusions

In present study, 21 criteria for assessing the sustainability of bioenergy systems for cooking were identified and ranked according to their importance by a multi-stakeholder panel in Uganda. The findings showed that economic and social dimensions are the major drivers of sustainability of bioenergy systems in the study area. The investment and operating costs were found to be the most important criteria for sustainability of bioenergy systems. The results of this study provides an important input to multi-criteria analysis (MCA) study for selecting bioenergy systems alternatives in order to achieve sustainability goals. As noted by Hajkowicz and Higgins (2008), problem structuring identification of decision options, criteria and criteria weights and is one of the most important step in MCA. Stakeholders panel are particularly important in the selection and assigning weights to criteria to be included in the study according to their perceived values, as demonstrated in this study. This study therefore makes an important contribution towards understanding of criteria of bioenergy for cooking in Uganda. In conclusion, for sustainable development of bioenergy for domestic cooking in Uganda, critical attention should be given to social and economic aspects of the sustainability. However, considerations should also include environmental and technical aspects of bioenergy systems.

Chapter 7 – Assessing the environmental impacts of Ugandan bioenergy systems

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Summary

Use of bioenergy could result in a variety of environmental impacts. The level of impacts could be an important parameter for decision makers when selecting energy systems or for policy making. In this chapter, the life cycle assessment methodology was used to evaluate the comparative environmental impacts of biogas, briquettes, charcoal and Jatropha energy systems under Ugandan conditions. It was found that the domestic biogas system was the most promising technology with lowest overall environmental impacts. However, results were greatly influenced by the choice of values allocation and system boundary. Recycling of by-products of biogas and Jatropha systems as fertilizer was observed to significantly improve their environmental performances. Future studies could consider evaluating the sustainability of these technologies by exploring their social, economic, environmental and technological aspects simultaneously in a decision framework.

7.1 Introduction

Developing countries heavily rely on solid fuels for cooking and heating. Most common solid fuels include firewood, charcoal, coal and agricultural residues. When used in the indoor environment, they lead to pollution, which is a major health risk factor to women and children who are often the most exposed. Charcoal in particular is more popular among urban users in developing countries because of its higher energy density and lower emissions than firewood. However, its production, transportation and use results in environmental pressures ranging from deforestation, loss of biodiversity and emissions of greenhouse gases (GHG) and air pollutants. This could result in adverse impacts on human health, land use and depletion of natural resources. Consequently, other technologies are currently being explored to supplement or substitute extensive charcoal use in developing countries. Amongst these technologies are the domestic biogas energy system, briquetting of biomass residues and use of plant oil.

Domestic biogas systems have of recent past attracted a lot of interest from policy makers in Uganda and other developing countries. Currently, there is deliberate effort by the government and development partners to promote the technology in Uganda. The technology provides opportunities for integration with crop production since slurry is a very good organic fertilizer. This is of great advantage, due to savings of energy, resources and emission along the supply chain of mineral fertilizers. The potential to mitigate atmospheric methane emission from decaying biomass material is another important advantage of the technology. Utilisation of biogas for cooking converts methane that could have been released to the atmosphere into carbon dioxide, which has a global warming potential of about 22 times less than that of methane. Nevertheless, methane emissions still occur along the biogas supply chains due to leakages in the systems. Emissions of pollutants also occur during processes such as feedstock production, and the use phase of biogas.

An alternative technology that is currently becoming of interest is briquetting of biomass residues to generate fuels for cooking. This may involve collection of agricultural residues over long distances to a central briquette production point. The collection, transportation and processing of residues into briquettes results in emissions of pollutants, which can lead to adverse environmental impacts. Material transportation phase leads to emissions of air pollutant and greenhouse gases (GHG). Depending on the distances involved, amount of emissions during transportation could be considerable, leading to adverse environmental impacts on human health and resource depletion. Like charcoal, combustion of briquettes in stoves results in emission of indoor air pollutants, such as particulate matter, and greenhouse gases.

Recently, plant oil based systems have also generated a lot of interest as a potential bioenergy for use in developing countries. Plant oil stoves have been developed, making it possible to directly use vegetable oils for cooking. Jatropha is one of the crops seen as a potential biofuel with even a potential to substitute fossil fuels in the transport sector. Jatropha cultivation could lead to land use change, and if carried out in forested area, could result in loss of carbon stock. Cultivation and processing into oil also requires energy and resources and is accompanied by emissions that could result in environmental impacts.

Since the processes involved in each of the four energy systems mentioned here vary in material and energy requirements, as well as emissions, one would expect each to have different levels of environment impacts. In order to combat the looming global warming and climate change, and ensure sustainability, the interest of a decision maker is; therefore, to minimise the environmental impact of a product or service. Products and services with the lowest environmental impact would be the best option from the environmental point of view. However, at the moment, there is lack of knowledge of the relative environmental performance of these energy systems used in Uganda.

The objective of this study was therefore to model and quantify the life cycle environmental impacts of biogas, briquettes, charcoal and Jatropha cooking energy systems using the life cycle assessment (LCA) methodology. A secondary objective was to generate key environmental performance indicators for each of the technology to be used as input to multi-criteria analysis study. The study used the attributional LCA approach (Rehl et al., 2012).

7.2 Methodology

The study followed the life cycle assessment (LCA) methodology. The LCA methodology was initially developed by the Society of Environmental Toxicology and Chemistry (SETAC) as an objective method for determining energy and material use, and release of wastes to the environment by a product, service or an activity (Klöpffer, 2006). Consequently, the International Organisation for Standardisation (ISO) developed a number of standards to guide LCA studies. Currently, the most authoritative LCA standards are the ISO 14040 and ISO 14044 (Finkbeiner et al., 2006). The LCA methodology is executed in four phases as follows: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment, and (4) life cycle interpretation.

7.2.1 Goal and scope of the study

The goal of this study was to carry out a comparative evaluation of the environmental impacts of four bioenergy technologies for domestic cooking in Uganda using the LCA methodology. Energy systems evaluated in the study were: (1) the domestic biogas system, (2) Jatropha plant oil using the *Protos* plant oil stove, (3) gasification of maize stalk briquettes in top-lit updraft (TLUD) gasifier stove, and (4) charcoal system involving combustion of charcoal produced from natural forests vegetation in the *Kenya Ceramic Jiko* (KCJ) stove. The charcoal system is the most widely used technology for domestic cooking in the study area and was therefore taken as the reference system. A functional unit of 1 MJ of heat effectively used for cooking was considered.

The scope of the study is from cradle-to-cradle, including impacts associated with material raw material production or extraction, material processing, transportation, use, management and recycling of by-products. The scope of the biogas system (Figure 7.1 (a)) included production of grass and using it for feeding cattle, and using the manure produced as substrate for biogas production. Two scenarios were developed, in the first, slurry discarded without recycling or reuse, while in the second it is used as an organic fertilizer to enhance grass production. Use of feed supplements, acaricides, and veterinary drugs for cattle treatment and maintenance were excluded from the scope of the study. The scope of gasification system (Figure 7.1 (b)) included the collection of raw material, transportation, drying and commutation, briquetting, and combustion in TLUD stoves. Raw material for briquetting was maize stalks, and was assumed to be a waste material, since it is usually burnt in open field, without energy recovery during land preparation for planting crops (Okello et al., 2013a). Operations and resource requirement for the production of maize was therefore excluded from the scope of the study. Also, disposal of ashes generated from the TLUD gasifier stove during the use phase was excluded from the system boundary, since it was assumed not to have any adverse environmental impacts (Bailis, 2005). Two scenarios were developed, in the first, biochar produced from TLUD stove is used as carbon sink, while in the second it is used to substitute charcoal for cooking.

Processes included in the boundary of charcoal systems were raw material extraction from natural forests, pyrolysis using traditional earth mound kilns, transportation to point of use and combustion in KCJ stoves (Figure 7.1 (c)). Like in the case of briquettes, disposal of ash was excluded from the system boundary. Being a reference system, only one scenario was evaluated. The Jatropha system boundary begins from Jatropha plant cultivation, harvesting of fruits, drying and threshing, oil extraction from seeds, and use of oil for cooking in the *Protos* plant oil stove (Figure 7.1 (d)). Two scenarios were developed and evaluated; the first assumed that seed cake is disposed without using as organic fertilizer, and husks generated during threshing is incinerated in open air. The second scenario assumed that seed cake is used as fertilizer and husks as substitute to maize residues for briquette production.

The geographical scope of the study was Gulu municipality, located in northern Uganda and surrounding areas within a radius of 40 km. Raw material production, collection, transportation, processing, use, and disposal is carried out within this radius.

Allocation was necessary in the biogas systems, in which cattle rearing results in production of milk for sale or consumption by households and manure used for biogas production. Economic allocation was used to distribute environmental impacts to the milk and manure. It was assumed that 10% of environmental impacts resulting from grass production and cattle keeping are associated with energy production and dairy products account for the remaining 90%.

7.2.2 Life cycle inventory

Life cycle inventory data for this study were mainly from secondary sources. Foreground data were mainly obtained from available literature for each of the technology under similar environment. Background data were obtained from ecoinvent 3.0 database. Details of the LCI analysis for each of the technology is given in Section 7.3.

7.2.3 Life cycle impact assessment

Eco-indicator 99 (Frishknecht and Jungbluth, 2007), a damage oriented approach for impact assessment was used in this study. The analysis included 11 environmental impacts, categorised under three endpoint impact categories of human health (carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer, ecotoxicity and acidification/eutrophication), ecosystem quality (land use) and resources (minerals and fossil fuels).

7.2.4 Life cycle interpretation

Interpretation of LCA results was performed using three different methods. For each technology, contribution analysis was carried out to identify environmental hotspots of the bioenergy supply chains. Also comparative plots of single score of impacts for each technology were done in order to understand the relative environmental impacts of the technologies. Lastly scenarios were developed for three technologies studied, except the reference system, by varying the systems parameters to observe their effects on the environmental impacts of each technology.

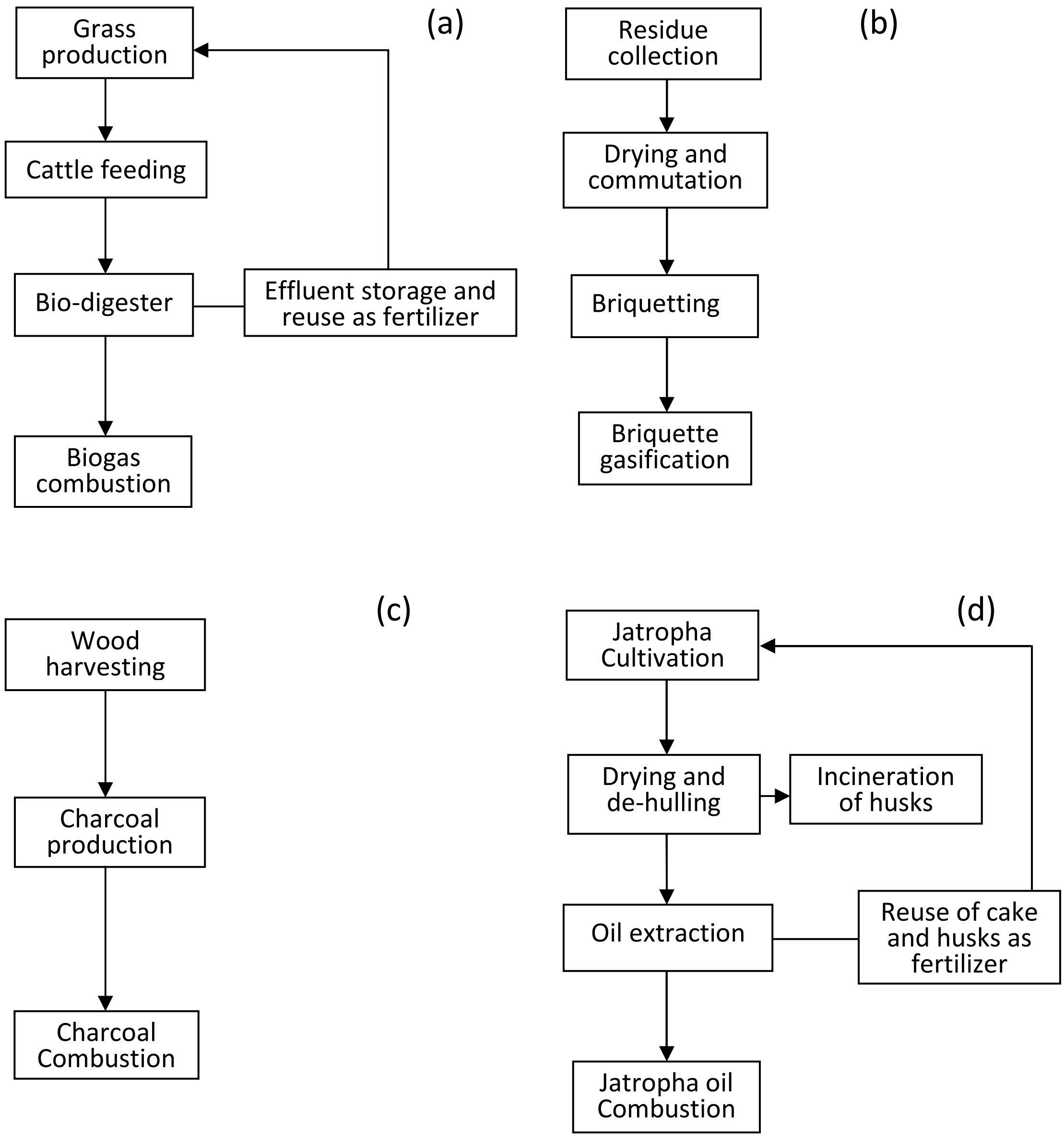


Figure 7.1. System boundary for the study; (a) biogas (b) briquette, (c) charcoal, and (d) Jatropha

7.3 Life cycle inventory analysis of the energy systems

7.3.1 Inventory of biogas system

Biogas technology is one of the priority bioenergy technologies being promoted for domestic cooking in the Uganda (Sengendo et al., 2010). In the renewable energy policy (2007), the country has set a target of installing 100,000 domestic biogas digester by the year 2017. Three different digester designs are available in Uganda, namely the fixed-dome, floating-dome and bag digester designs. The fixed-dome also called Chinese digester is the most commonly used. The digester is built underground of masonry, and usually range in volume from 8 to 16 m^3 (Okello et al., 2013b; Walekhwa et al., 2009).

Cattle manure is the most commonly used substrate for biogas production in Uganda. In this study, the biogas system was modelled from the stage of Napier grass (*Pennisetum Purpureum*) cultivation as a feedstock to cattle kept under zero-grazing. Manure generated by the cattle is mixed with water in a ratio of 1:1 by volume and a fixed amount fed into the bio-digester on a daily basis. Dilution of manure with water enhances gravitational flow of substrate through the system; therefore, avoiding need for mechanical pumping operations. Gas from the storage chamber of the digester is conveyed through pipes and used for cooking using biogas burners.

Cultivation, weeding and harvesting of grass are typically manual operations in Uganda. Grass production was assumed to be under rainfed conditions without supplementary irrigation input. To maintain yield, mineral fertilizers are applied to grass. The annual requirement of fertilizer for grass production was taken as 200 kg ha^{-1} of calcium ammonium nitrate (CAN), triple superphosphate (TSP) or single superphosphate (SSP) at a rate of 300 kg ha^{-1} and Muriate Potash (KCL) at a rate of 80 kg ha^{-1} (Orodho, 2006). All operations were assumed to take place within the farm premises and therefore, vehicles were not used for transportation of materials. The grass yield was taken to be 8000 kg dry matter per hectare in accordance with Lukuyu et al., (2012).

A typical head of cattle weighing 400 kg and requiring 12 kg dry matter feed per day was assumed. Rearing of cattle results in enteric methane emissions, which in accordance with Casey and Holden, (2005) was assumed to be 100 kg y^{-1} per cattle head. Dry matter (DM) content of manure was assumed to be 15%, and biogas yield from manure is assumed to be 0.281 kg kg^{-1} of DM. Since the digester is not fully airtight, some methane loss occurs during digestion through openings such as the substrate inlet pipe and slurry expansion chamber (Khoiyangbam et al., 2004). Estimated methane loss from fixed and floating dome digesters range from 5 to 15% of total methane yield (Griggs and Noguer, 2002; Pathak et al., 2009). Methane emission from the CARMATEC bio-digester was estimated using the mid value of 10% leakage.

The use phase of the biogas system involves combustion of the gas in burners. Burners are of several designs, some of which are locally fabricated by Ugandan artisans and their emissions and efficiencies are expected to vary with design. For this study, it was assumed that the efficiency of biogas burner is 55% (Sasse et al., 1991). Heating value of biogas was assumed 20 MJ kg^{-1} and density as 1 kg m^{-3}(Perera et al., 2005). Combustion of biogas results in emissions such as CO_2, CH_4, NOx and particulate matter. Emission factors from biogas burners were adopted from Afrane and Ntiamoah (2012) and (Smith et al., 2000).

Table 7.1. Input and emissions LCI data for the biogas system (per MJ heat effectively used for cooking)

Process	Inputs and outputs	Quantity per MJ of heat	Units
Grass cultivation	*Input*		
	N as Calcium ammonium nitrate (CAN)	3.78E-02	kg
	P as Single/triple superphosphate (Mono-calcium phosphate)	5.66E-02	kg
	K as Muriate Potash (Potassium chloride KCL)	1.51E-02	kg
	Land occupation	1.888	m^2
	Output		
	Grass (dry matter)	1.51	kg
Cattle Feeding	*Inputs*		
	Grass (dry matter)	1.51	kg
	Water	8.808	L
	Outputs		
	Enteric methane emission	3.45E-02	kg
	Manure (dry matter)	3.59E-01	kg
Biogas production	*Inputs*		
	Water	2.3933	L
	Manure (dry matter)	3.59E-01	kg
	Outputs		
	Methane emissions	6.00E-03	kg
	CO_2 emissions		kg
	Biogas	9.10E-02	kg
Biogas combustion	*Inputs*		
	Biogas	9.10E-02	kg
	Output (emissions kg MJ^{-1})		
	CO_2	1.47E-01	kg
	CO	2.03E-04	kg
	NOx	9.15E-05	kg
	N_2O		
	SO_2	1.02E-05	kg
	NMVOC	6.10E-05	kg
	CH_4	1.02E-04	kg
	PM	4.82E-06	kg
Effluent management	*Inputs*		
	Effluent (volume)	4.790	L
	Outputs		
	NH_3	5.500E-04	kg
	CH_4	3.218E-03	kg
	N_2O	7.467E-05	kg

Slurry is the by-product of the digestion process and it flows by gravity from the expansion chamber into a storage tank. It is rich in essential plant nutrients, with the DM comprising of 1.4% nitrogen, 0.5% phosphorus, and 0.8% potassium (Pathak et al., 2009). In the second scenario of this study, was slurry modelled to substitute mineral fertilizers by applying it in the grass fields. Application of slurry was assumed to be manually done, so does not require machinery operations. However, the slurry emits gases such as NH_3, CH_4 and N_2O during storage and application in crop fields (Boulamanti et al., 2013).

Total emissions of NH_3, CH_4 and N_2O during storage and application were assumed to be 229.9 g m^{-3}, 1344.6 g m^{-3} and 31.2 g m^{-3}, respectively (Amon et al., 2006). It was assumed that negligible loss in mass of the substrate occurs during digestion (Pathak et al., 2009). Therefore, the volume DM content of slurry was assumed to be equivalent to that of the initial substrate material fed into the digester.

Based on these assumptions and secondary data presented here, the foreground inventory data of the biogas system were developed and presented in Table 7.1. Background data for the system was obtained from the ecoinvent LCA database.

7.3.2 Inventory of the gasification system

Biomass briquetting is the conversion of loose biomass material into a high density product by subjecting the material under pressure, with or without binder (Mwampamba et al., 2013). The briquetting process involves material collection, drying, commutation and densification using various types of presses (Samson et al., 2005). The resulting product is called briquette and is easier to handle and has better combustion properties than the original biomass material. Uganda generates large quantities of agricultural and forest residues that could be used as raw material for briquette production (Knöpfle, 2004; Okello et al., 2013a). According to studies by Okello et al., (2013a), the gross energy potential of maize stalk in Uganda amounts to 65.5 PJ y^{-1}, and is the highest of all the crops residues evaluated in the study. Maize stalk was therefore chosen as the raw material for briquettes production in this study.

Maize stalk used for briquettes production was assumed to be an agricultural waste with no value attached. Actually, the stalks are usually burnt in open field during land preparation for subsequent crop planting. Therefore, resources for production of maize, such as mechanical power and fertilizers were excluded from the boundary of the current study. However, maize is grown by individual farmers spread over a large geographical area surrounding Gulu municipality. This therefore requires that it is collected to a central point for processing into briquettes. Since most rural areas surrounding the municipality do not have access to electricity, it was assumed that all processing operations take place within Gulu municipality. It was assumed that collection of maize residues is done within an average distance of 40 km from the processing plant using a truck of 16 tonne capacity. Use of trucks results in emissions, which was estimated using ecoinvent 3.0 databases.

Upon arrival at the processing plant, the maize stalk undergoes drying and commutation into suitable particle size for briquetting. The study area receives on average global solar radiation ranging from about 5 kWh m^{-2} d^{-1} in July, to about 6 kWh m^{-2} d^{-1} in January (Mubiru and Banda, 2012). Therefore, it was assumed that drying of the maize stalk was primarily done using solar energy, without additional energy inputs from the technosphere. Size reduction was assumed to be accomplished by a hammer mill, powered by electrical energy from the grid. Energy requirements for commutation of maize stalk was taken to be 18 kWh t^{-1}, and for briquetting as 43 kW t^{-1} of briquettes produced (Hu et al., 2014). Upon production, the briquettes are distributed to users within the municipality at an average distance of 10 km using a 16 tonne truck.

Upon manufacture, the briquettes are directly used for cooking using gasifier stoves. Gasification process was modelled using the TLUD gasifier stove. The TLUD stove was chosen for the study because it known to be more fuel efficient and emits less air pollutant than traditional charcoal and firewood stoves used in Uganda (Martin et al., 2013). According to Ravindranath and Balachandra, (2009) efficiency of TLUD gasifier stove range from 25% to 35%; thus, for this study, a mid value of 30% was assumed. Combustion of briquettes in TLUD stoves results in emissions such as CO_2, CO, CH_4, and particulate matter. Emission factors for the stove where obtained from (Sparrevik et al., 2013).

Gasification of briquettes in TLUD stoves results in charcoal and ash as by-products. The recovery rate of charcoal produced was estimated to be 28% of the input biomass (Sparrevik et al., 2013). The charcoal can be used as fuel for cooking in charcoal stoves. Alternatively, the charcoal can be used as soil amendment to improve crop yields. Use of charcoal as carbon sink, for long-term storage of carbon to mitigate atmospheric greenhouse gas emission is also gaining interest amongst scientific community (Sparrevik et al., 2013). Disposal of the ash generated was assumed not to cause any significant environmental impacts (Bailis, 2005).

Using the assumptions and data available from literature cited in this section, the foreground inputs data for the LCA was calculated for a functional unit of 1 MJ heat and presented in Table 7.2. Secondary data used for the LCA was obtained from the ecoinvent database.

Table 7.2. Input and emission inventory data for briquetting system

Process	Inputs and outputs	Quantity per MJ of heat	Units
Residue collection	*Input*		
	Transport 16 ton truck	9.68E-03	tkm
	Output		
	Maize stalk	2.42E-01	
Drying and commutation	*Inputs*		
	Electricity (100% Hydro)	4.36E-03	kWh
	Outputs		
	Maize stalk particles	2.42E-01	kg
Briquetting	*Inputs*		
	Electricity	1.04E-02	kWh
	Outputs		
	Briquettes	2.42E-01	kg
Briquette distribution	Input from techno-sphere		
	Transport		kg
	16 t truck	2.42E-03	tkm
Briquette combustion TLUD gasifier stove, 30% efficiency	*Inputs*		
	Briquettes (3.333MJ heat)	2.42E-01	kg
	Output		
	Useful heat (product)	1.00	MJ
	Co-product (Biochar/kg briquettes)	3.600E-01	kg
	Combustion emissions per kg feedstock		
	CO_2	7.604E-01	kg
	CO	1.483E-02	kg
	NOx	4.840E-06	kg
	N_2O	9.680E-06	kg
	SO_2	0.000E-00	kg
	NMVOC	6.171E-03	kg
	CH_4	2.977E-03	kg
	$PM_{2.5}$	1.137E-03	kg

7.3.3 Inventory of charcoal – the reference system

The charcoal system was modelled based on the current system of charcoal production, which involves harvesting of wood from natural forest, followed by pyrolysis in the traditional earth-mound kilns. The charcoal is then transported using trucks to the urban areas for cooking in charcoal stoves. All the harvesting and charcoal production operations are manually done using simple tools, such as axes, hoes and machetes. The wood harvesting stage involves extracting entirely above ground portion of the vegetation and therefore could result in variation in carbon stock. Carbon stock flux due to wood harvesting of -1.43 t C per tonne of charcoal produced from native vegetation on a 15 year coppice was assumed for this study (Bailis, 2005). Not all the above ground biomass harvested is converted into charcoal. Small branches and leaves that is not suitable for charcoal production is burnt in open fire in the forest, or in some cases collected and used as firewood for cooking. In this study, it was assumed that unsuitable wood, estimated to be about 10% of the mass of the total harvested biomass is burnt in open air. This results in air emissions that was estimated to be equivalent to open fire burning under savannah conditions (Akagi et al., 2011).

Carbonisation was assumed to be in traditional earth-mound kilns. It is the most common technology for charcoal production in Uganda as well as other sub-Saharan African countries. It involves stacking the harvested wood in piles and covering with soil to limit the oxygen supply during pyrolysis. The efficiency of the process ranges from about 10 to 15% (Knöpfle, 2004; Okello et al., 2013b). The worst-case scenario of 10 % efficiency of charcoal recovery was used for modelling charcoal production in this study. Carbonisation process results in emissions of gases such as CO_2, CO, CH_4, NMVOC and particulates. Emission factors for charcoal production in earth-mound kilns were obtained from Pennise et al., (2001).

Charcoal is then packed in polythene bags and transported using trucks to the urban area where it is used for cooking. It was assumed that a 16 tonne truck is used for transportation of charcoal and the emission factors were obtained from the ecoinvent database. Transportation results in GHG and pollutant emissions. An average charcoal collection distance of 40km was assumed, with the truck travelling empty in the return trip.

Use of charcoal is by combustion in charcoal stoves, resulting in emissions of pollutants and greenhouses gases such as emissions CO_2, CO, CH_4, NMVOC and particulates (Bhattacharya et al., 2002). Level of emissions depends on the design of the stove. Kenya *Ceramic Jiko* is a commonly used charcoal stove in Uganda and was therefore used in modelling the combustion process. Emission factors for cooking with charcoal in KCJ stove was obtained from Jetter et al., (2012). Stove thermal efficiency at cold start of 15% (Oketch, 2012) was assumed, and the calorific value of charcoal was assumed to be 30.8 MJ kg^{-1} (Bhattacharya et al., 2002).

With the assumptions presented in this section, foreground data for producing 1 MJ of heat energy effectively used for cooking was calculated and presented in Table 7.3. Secondary data such as emissions from trucks during transportation was obtained from ecoinvent database.

7.3.4 Inventory of Jatropha system

Under this system, a plantation of Jatropha (*Jatropha curcas*) is established for production of Jatropha oil. Jatropha can be planted on marginal land, or intercropped with food crops in an agro-forestry system (Contran et al., 2013). Cultivation of Jatropha requires input of NPK fertilizer. However, as noted by Achten et al., (2008) the application rate has not yet been optimised. For this study we assumed an annual application rate of 81 kg ha^{-1} nitrogen as N, 31 kg phosphorus as P_2O_5, and 89 kg potassium as K_2O (Eshton et al., 2013). Annual yield of 5000 kg of dry Jatropha seed per hectare was assumed. All the field operations were assumed to be manually done and being a tropical climate, irrigation is not required during Jatropha cultivation. Harvested fruits are transported using a 16 tonne truck to a central processing point at a mean distance of 40 km from the fields.

Table 7.3. Input and emissions inventory data for the charcoal system

Process	Inputs and outputs	Quantity per MJ of heat	Unit
Wood harvesting	*Input*		
	Natural forest vegetation (dry)	2.9630	kg
	Output		
	Net CO_2 flux due to direct land use change	-5.83E-04	kg
	Dry wood for charcoal	2.66667	kg
	Wood waste (10%) of total	2.96E-01	kg
	Emissions from open air wood waste combustions		
	CO_2	5.00E-01	kg
	CO	1.87E-02	kg
	NOx	1.16E-03	kg
	NH3	1.54E-04	kg
	N_2O	0.00E+00	
	SO_2	1.42E-04	kg
	NMVOC	1.40E-02	kg
	CH_4	5.75E-04	kg
	PM2.5	2.12E-03	kg
Charcoal production (pyrolysis) in earth mound kilns, 12.5% efficiency	*Inputs*		
	Dry wood	2.66667	kg
	Outputs		
	Charcoal	0.33333	kg
	Emissions		
	CO_2	6.01E-01	kg
	CO	7.43E-02	kg
	NOx	2.10E-05	kg
	NO	1.87E-05	kg
	N_2O	5.00E-06	kg
	SO_2	0.00E+00	
	NMVOC	3.09E-02	kg
	CH_4	1.49E-02	kg
	PM (TSP)	1.01E-02	kg
Transport	*Inputs*		
	16 t truck	1.00E-02	
Charcoal combustion, Ceramic Jiko stove, (10% efficiency), 15% efficiency	*Inputs*		
	Charcoal (equivalent to 5.56MJ heat)	3.33E-01	kg
	Output		
	Heat (product)	1.00	MJ
	Emissions (Per MJ heat effective)		
	CO_2	6.96E-01	kg
	CO	6.57E-02	kg
	NOx	3.33E-05	kg
	N_2O	0.00E+00	
	SO_2	0.00E+00	
	NMVOC	3.40E-03	kg
	CH_4	4.17E-03	kg
	PM2.5	1.32E-03	kg

Jatropha fruit then undergoes processing involving sun-drying and de-hulling, oil extraction and purification. Due to favourable levels of insolation in the study area, drying is carried out under natural conditions in the sun. Dry Jatropha fruit is composed of 35 to 40% husks, and 60 to 65% seeds which has an estimated oil content of 34.4% (Achten et al., 2008). Oil extraction is carried out using expellers, such as “Sundhara” oil expellers, which are designed for a variety of oil seeds (Grimsby et al., 2012). The efficiency of oil extraction by hand press is about 60% (Brittaine and Lutaladio, 2010). In the last processing stage, impurities in the oil are then allowed to settle by gravitation before being filtered through a piece of cotton cloth. Filtered oil can be directly used in plant oil stoves for cooking. The oil can also be further processed through esterification to produce biodiesel, or saponification to produce soap. In this study, it was assumed that filtered oil is directly used for cooking using plant oil stoves.

Jatropha fruit husks and seed cake are by-products generated during de-hulling and oil extraction processes, respectively. The husks have an energy content of 16.5 MJ kg^{-1} (Eshton et al., 2013), and can be densified into briquette fuel for cooking. In the first scenario, it was assumed that the husks are disposed of by open burning, which is a common practice for disposing of agricultural wastes in Uganda. This results in emissions, which are estimated to be equivalent to those of other agricultural residues (Akagi et al., 2011; Estrellan and Iino, 2010). Seed cake is known to be a good quality fertilizer (Openshaw, 2000), with composition of 4.91% N, 0.90% P and 1.75% K (Pandey et al., 2012). Alternatively, the cake can be used as a substrate for biogas production, or as a raw material for synthetic fibre production. In this study, we assumed that all the cake is used as a substitute to inorganic fertilizer for Jatropha cultivation.

Combustion was modelled to take place in a plant oil pressure stove called *Protos* (Gaul, 2013; Kratzeisen and Müller, 2009). The density and heating value of Jatropha oil were assumed to be 932.92 kg m^{-3} and 38.2 MJ kg^{-1}, respectively (Pramanik, 2003). Meanwhile, the thermal efficiency of the Jatropha stove was assumed to be 40% (Huboyo et al., 2013). It was assumed that emissions from *Protos* stove are equivalent to that of Rapeseed combustion in *Protos* stove. This is because the data for Jatropha oil combustion in plant oil stoves is currently not available.

With the sets of assumptions presented in this section, the foreground inventory data for Jatropha system, required to generate 1 MJ cooking energy was calculated and presented in Table 7.4. Background data for emissions due to fertilizer application and transport was obtained from the ecoinvent 3.0 database.

Table 7.4. Input and emissions inventory data for Jatropha system for 1 MJ of heat energy

Process	Inputs and outputs	Quantity per MJ of heat	Units
Jatropha cultivation	*Input*		
	Nitrogen fertilizer as N	5.13E-03	kg
	P as single/triple superphosphate	1.96E-03	kg
	K as Muriate Potash	5.64E-03	kg
	Pesticide, delta 2.5% Emulsion Concentrate	2.09E-02	ml
	Land occupation	6.34E-01	m^2
	Output		
	Jatropha fruits	5.28E-01	kg
Drying and de-hulling	*Inputs*		
	Jatropha fruits	5.28E-01	kg
	Outputs		
	Jatropha seeds	3.17E-01	kg
	Jatropha husks	2.11E-01	kg
Oil extraction efficiency 60%	*Inputs*		
	Dry Jatropha seed, 34.4% oil content	3.17E-01	kg
	Outputs		
	Jatropha oil	6.54E-02	kg
	Jatropha seed cake, 12.30% oil content	2.51E-01	kg
Jatropha oil combustion, *Protos* plant oil stove, efficiency 40%	*Inputs*		
	Jatropha oil (equivalent to 2.5MJ gross)	6.54E-02	kg
	Output (emissions kg kg^{-1} oil)		
	CO_2	2.47E-01	kg
	CO	1.85E-03	kg
	NOx	1.70E-04[b]	kg
	N_2O	1.85E-07[a]	kg
	SO_2	3.50E-04[b]	kg
	NMVOC	3.75E-05[b]	kg
	CH_4	1.90E-04	kg
	$PM_{2.5}$	3.93E-04	kg
Seed cake and husks management	*Inputs*		
	Husks	2.11E-01	kg
	Cake	2.51E.01	kg
	Outputs (emissions from husks incineration)		
	CO_2	3.35E-01	kg
	CO	2.15E-02	kg
	NOx	6.57E-04	kg
	N_2O	1.48E-05	kg
	SO_2	4.22E-04	kg
	NMVOC	1.63E-02	kg
	CH_4	2.53E-04	kg
	$PM_{2.5}$	1.32E-03	kg

[a] EPA database (http://www.epa.gov/climateleadership/documents/emission-factors.pdf),
[b] Calculated from Air Pollutant Emission Factor Library, assuming energy production from small combustion equipment in Europe, using liquid fuels for residential application (equipment type – other). (http://www.apef-library.fi/).

7.4 Results and discussions

In this section, the results of the environmental impact assessment of the four energy systems are presented. The results are divided into two main sections: Section 7.4.1 presents results of the baseline scenario, and in Section 7.4.2, results of alternative scenarios involving resource by-product recycling modelled through system expansion are presented.

7.4.1 Characterisation results

Environmental impacts were characterised and results for each of the technology is presented in Table 7.5 and Figure 7.2. Characterisation results show that biogas system had the highest impact categories of radiation, acidification and eutrophication impacts compared to the other energy systems. Charcoal system on the other hand ranked highest in impact categories of carcinogens, respiratory organics and inorganics and climate change impacts. Jatropha system had highest impact categories of ozone layer, ecotoxicity, land use, minerals and fossil fuels.

Table 7.5. Comparative characterised results of the environmental impacts of the four energy systems under baseline scenario using Eco-indicator 99 impact assessment method

Impact category	Unit	Biogas cooking	Briquette gasification	Charcoal cooking	Jatropha oil cooking
Carcinogens	DALY	8.59E-09	1.27E-08	3.39E-08	2.82E-08
Respiratory organics	DALY	2.29E-10	7.94E-09	6.21E-08	2.1E-08
Respiratory inorganics	DALY	8.18E-08	8.1E-07	2.66E-06	1.37E-06
Climate change	DALY	4.73E-08	1.19E-08	8.43E-08	1.45E-08
Radiation	DALY	1.02E-10	6.45E-12	6.85E-12	8.71E-11
Ozone layer	DALY	1.61E-12	4.44E-13	5.19E-13	4.13E-12
Ecotoxicity	PAF*m2yr	8.90E-03	2.64E-03	8.14E-04	1.57E-02
Acidification/ Eutrophication	PDF*m2yr	9.88E-03	1.45E-04	9.78E-03	7.06E-03
Land use	PDF*m2yr	1.09E-01	6.12E-05	5.82E-05	7.30E-01
Minerals	MJ surplus	1.48E-03	3.14E-04	4.10E-05	2.45E-03
Fossil fuels	MJ surplus	1.66E-02	3.28E-03	3.77E-03	3.82E-02

Results presented in this section are indicators of each impact category over the entire supply chain of each technology; therefore they cannot explain the specific processes contributing to the impacts. Also, it can be observed that the results presented in Table 7.5 have different units. These have been converted into percentage values, to illustrate the relative environmental impacts of the four technologies shown Figure 7.2. Each impact category has not been assigned relative importance of their impacts on the environment and therefore cannot be used as a basis for selection or ranking of the technologies. However, they provide insight to the impacts of each technology relative to each other, and therefore important to identification of impact hotspots per technology.

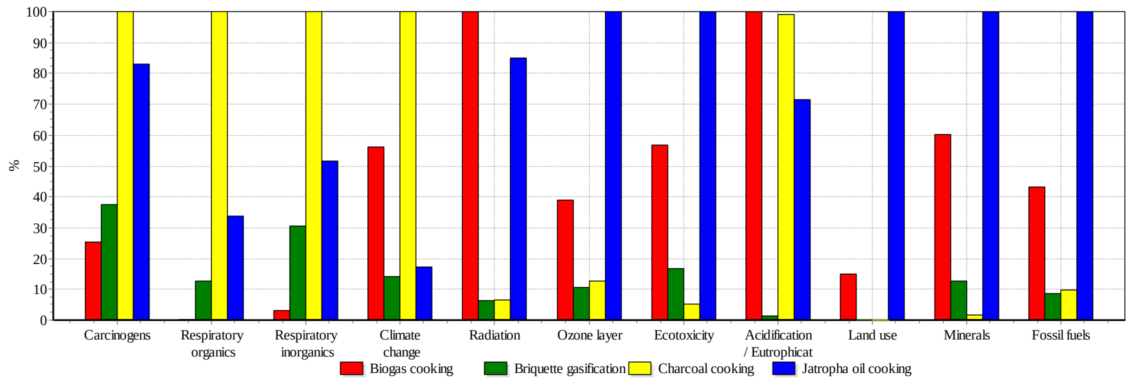
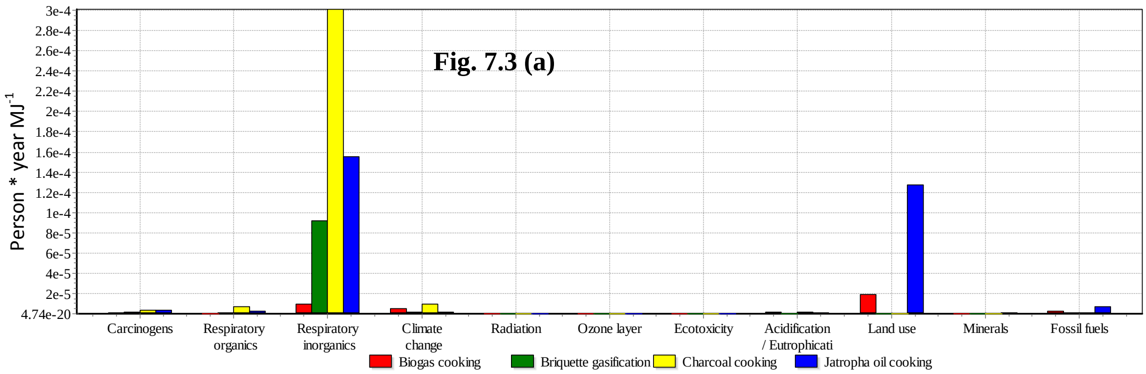


Figure 7.2. Relative environmental impacts of producing 1MJ of cooking energy from biogas, briquette gasification, charcoal and Jatropha systems

7.4.2 Normalised results of the environmental impacts of the technologies

Normalisation stage of LCIA expresses the impact and damage categories of a product LCA in a form that allows for comparison of their relative severity in comparison to a reference value. Unlike characterisation, the normalised results presented in Figure 7.3 (a) and (b) have the same units. This therefore allows for comparing the contribution of particular impact or damage category to global environmental burdens in comparison with a reference normal value. Figure 7.3 (a) shows that the environmental impacts of respiratory inorganics of the charcoal system has the highest environmental load, followed by that for Jatropha system and then briquette gasification. This could be explained by the high levels of emissions of particulates, SO_2 and NOx during combustions process. The land use impact category for Jatropha system is relatively higher than those for charcoal, biogas and briquette gasification systems. This can be explained by the land requirements for Jatropha. However, radiation, ozone layer, ecotoxicity and minerals impact categories are all very close to reference levels.

Figure 7.3 (b) gives the results of normalisation per damage categories human health, ecosystem quality and resources for each of the energy systems. It indicates that charcoal system has the highest damage to human health with a value of about 3.25E-04 person*year per MJ of cooking energy. Damage to human health by Jatropha system is however lower than that of charcoal by about 50%. Jatropha on the other hand has the highest damage to the ecosystem quality followed by biogas systems. This is perhaps explained by land requirements for Jatropha plant cultivation, and for biogas is also probably due to land occupation for grass cultivation needed for cattle feeding.



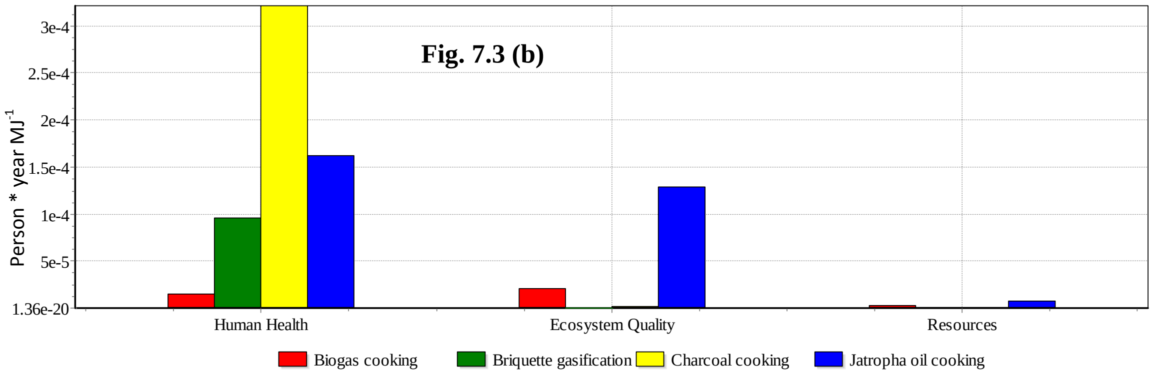


Figure 7.3. Normalised results of the comparative environmental impact of producing 1 MJ of cooking energy – (a) indicators of the 11 impacts categories, (b) indicators per damage categories

7.4.3 Comparison of single scores of environmental impacts

Results presented in Figure 7.4 shows the single score of the environmental impacts of the four cooking energy system. This is obtained by aggregation of the 11 impact categories using Eco-indicator 99 method to enhance the comparison of the total damage to the environment by each of the technology. Figure 7.4 (a) shows that Jatropha system has the highest potential damage to the environment, mainly due to land use and respiratory inorganics which together contribute over 90% of the total Eco-indicator points of the system. Respiratory inorganics have severe impacts on human health, resulting in very high damage to human health by the charcoal system as shown in Figure 7.4 (b). Severity of the environmental damage of the charcoal system is second to that of Jatropha system. However, the damage is primarily due to respiratory inorganics such as SO_2 and NOx, which contribute over 90% to the total damage of the charcoal system. The results show that briquette gasification and biogas system have the less environmental damage compared to the charcoal and Jatropha systems. However, like charcoal system, respiratory inorganics are the predominant contributing factor to the environmental damage by briquettes gasification. The lower impact levels are perhaps explained by the lower emission levels of the TLUD gasifier stoves.

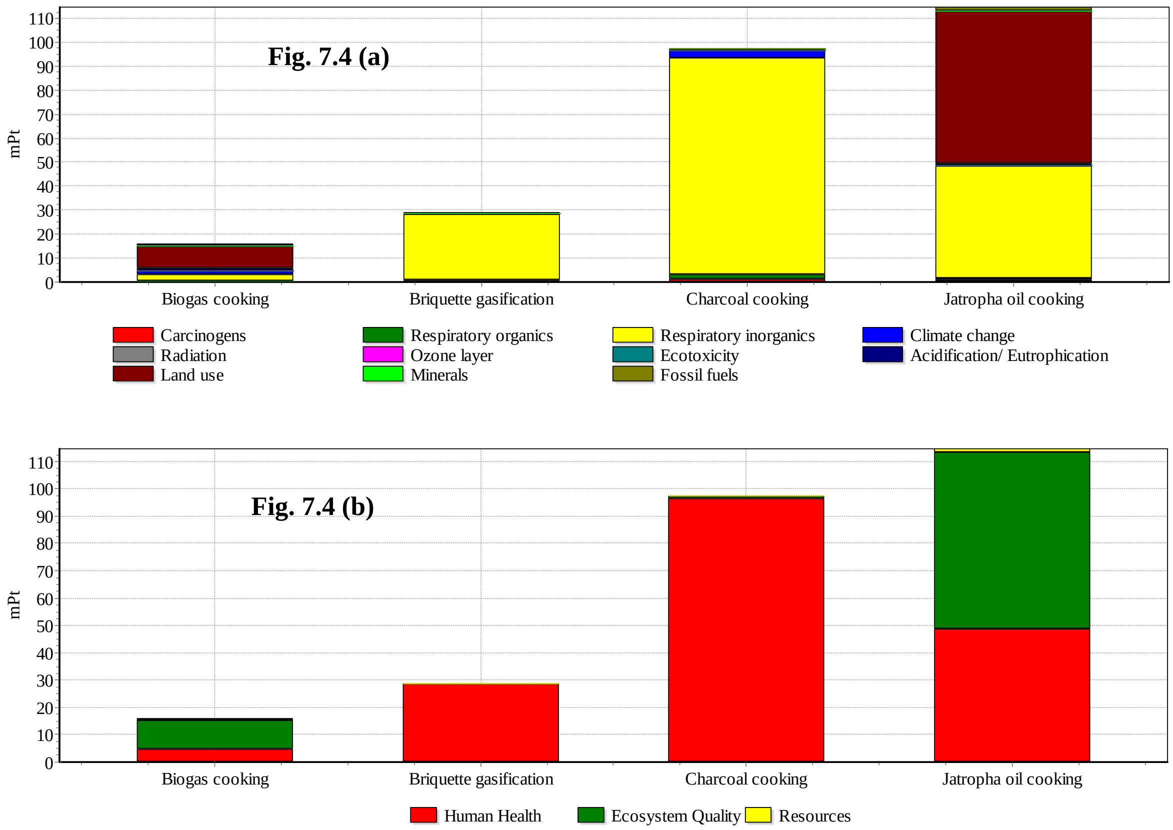


Figure 7.4. Comparison of environmental impacts, single scores: (a) results showing impact categories (b) results showing damage categories

7.4.5 Contribution of systems processes to environmental impacts

In this section, the contributions of individual processes to the total impacts of each system are presented. Results of process contribution for the technologies to their total environmental impacts are given in Figure 7.5. Grass cultivation had the highest contribution to the environmental impacts of the biogas energy system shown in Figure 7.5 (a). The results of biogas presented assume a physical allocation of 5% of the environmental impacts of grass cultivation is attributed to manure production. The other 95% is attributed to dairy products resulting from cattle kept for manure. However, if it is assumed that manure is a waste with no value, then impacts from grass cultivation will fall to zero. Increasing the allocation of environmental impacts of grass cultivation will on the other hand significantly increase the impact of grass cultivation stage. Major impacts of cultivation of grass are land use and emissions from fertilizer application. This suggests that reducing mineral fertilizer use in grass cultivation phase would reduce environmental impacts of the process. Biogas production process also has a contribution of 3.5 mPt, which is quite high in comparison to cooking process with impact of less than 1 mPt. This can be explained by emissions of methane due to leakage from parts of biogas digesters that are not fully sealed. Additional contribution is from emissions of NH_3, CH_4 and N_2O from slurry storage.

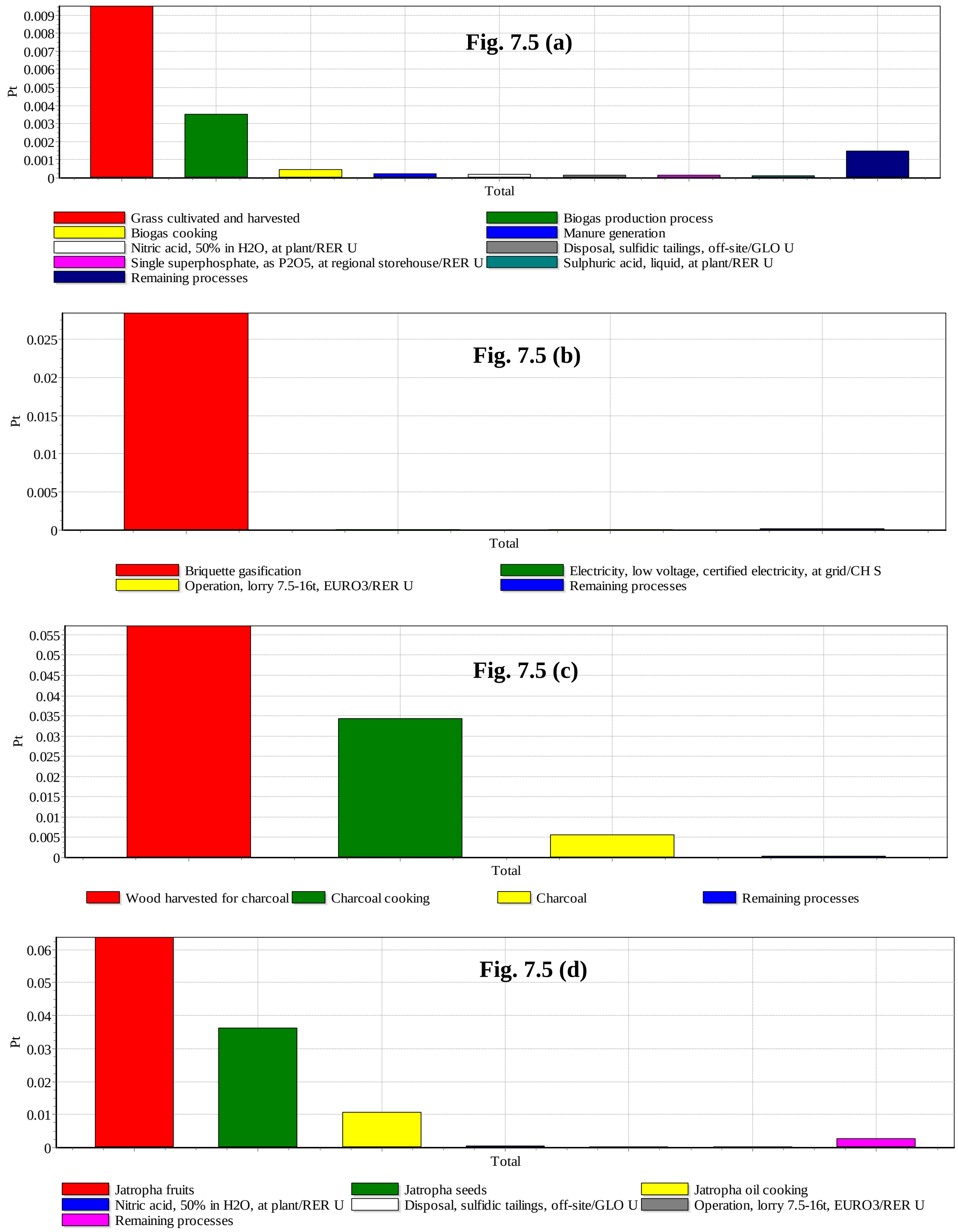


Figure 7.5. Process contribution analysis; (a) biogas, 0.67% cut-off (b) gasification, 0.2% cut-off (c) charcoal, 0.2% cut-off (d) Jatropha at 0.2 % cut-off

Figure 7.5 (a) further shows that the cooking stage has a relatively low impact of less than 1 mPt, which can be explained by the relatively low emissions from biogas combustion. This suggests that the cooking process using biogas would result in lower health impacts on users.

Contributions of different processes to the total impacts for the briquette gasification system are shown in Figure 7.5 (b). The figure suggests that the largest environmental load for this system is during the use phase. This is due to emissions of gases during combustions of briquettes in the TLUD gasifier stove. Total impacts due to the use phase is about 30 mPt, which is much higher than cooking with biogas, which is less than 1 mPt. Other processes such as transport, and electricity did not contribute significantly to the total environmental impacts of the system. It is important to note that residue collection could result in reduced soil organic matter content, therefore reducing its productive capacity. Agricultural residues also contribute to reducing soil erosion, increasing activity of soil organisms that help to ensure improved soil productivity. These impacts were not modelled in the present study, due to lack of suitable modelling data. The actual impact of the briquette system could therefore be much higher than that depicted in this study.

Figure 7.5 (c) shows results of the process contribution analysis for the charcoal system. It indicates that wood harvesting process, with impact of about 55 mPt is the highest environmental impacts in the charcoal supply chain. This is mainly attributed to emissions resulting from open air burning of wood debris that remains in the forest after wood harvest. Next in level of environmental impact is the cooking process with an impact of about 35 mPt, which arise as a result of emissions from KCJ during cooking. This is a major concern since the emission takes place in the indoor environment leading to indoor air pollution, a major cause of ill health amongst solid fuel users in developing countries. The results further show that the charcoal making process contributes less environmental impacts compared to the wood harvesting and cooking processes. These results suggest the need to improve wood residue management during harvesting, reducing the emissions of cooking stoves and followed by the charcoal pyrolysis process. The latter two could be achieved by adopting better technologies, while the former by improving residue management practices.

For Jatropha system, the cultivation process had the highest environmental impact, of about 63 mPt as shown in Figure 7.5 (d). Like in the case of biogas system, factors responsible for this are land use and fertilizer application. Further improvement could be achieved by intercropping Jatropha plant with crops, under agro-forestry system. Also recycling of Jatropha seed cake as a fertilizer could probably reduce the environmental impacts due to mineral fertilizers. This is investigated in Section 7.3.2. Next in importance is the environmental impact due to Jatropha seed extraction. This is perhaps explained by emissions from open air burning of Jatropha seed husks. Better utilisation method of the seed husks, such as use for briquette production could most likely result in improved environmental performance of the Jatropha system. In Section 7.3.2, effect of using Jatropha seed husks to substitute maize stalk residues is investigated, through system expansion.

Of interest to compare are environmental impacts resulting from the use phase of each of the technology. This is because the emissions that cause these impacts occur in the indoor environment, therefore pausing serious health risks to users. Cooking with biogas had the lowest impact of about 0.5 mPt followed by Jatropha oil, briquette gasification and charcoal with 10 mPt, 30 mPt, and 35 mPt, respectively. This suggests that cooking with biogas has lower health impacts due to indoor air pollution than the other three energy systems.

7.5 Analysis of scenarios and suggestions for reducing environmental impacts

In this section, alternative scenarios of biogas, briquette gasification, and Jatropha oil systems were developed and the results are presented. The aim was to investigate any possible improvement to the energy systems. Scenario B of the biogas system was based on the assumption that manure is waste material with no economic value attached to it. Therefore, grass cultivation process was assumed not to contribute to the impacts of biogas production. Also, all slurry produced from the digestion process is used as fertilizer to substitute mineral fertilizer. This was modelled through system expansion. Scenario B of the briquette system was developed by taking into consideration that charcoal generated from cooking with TLUD stove is used to substitute forest charcoal. System expansion was used to model the substitution process. For Jatropha system, scenario B assumed that seed husks generated during de-hulling substitutes maize stalk for briquette production, unlike in the previous case where they were burnt in open air.

Also, all the seed cake generated during Jatropha oil extraction is used as substitute to NPK mineral fertilizer, and was modelled through system expansion. The charcoal system was kept constant as a reference system.

7.5.1 Characterisation results of comparative scenarios

Characterisation results of the baseline scenario A and the alternative scenario B with recycling and system expansion is given in Figure 7.6. It indicates that scenario B of biogas, Jatropha oil and briquette gasification show reduction in characterisation values for majority of the impact categories. Both biogas and Jatropha oil systems registered negative values for carcinogens, radiation, ozone layer, ecotoxicity minerals and fossil fuels. These are perhaps explained by the substitution of mineral fertilizers by slurry for the case of biogas production, and by seed cake for Jatropha, which results in reduced environmental impacts of mineral fertilizers. Overall, scenario B showed reduction in environmental impact categories for all the three technologies.

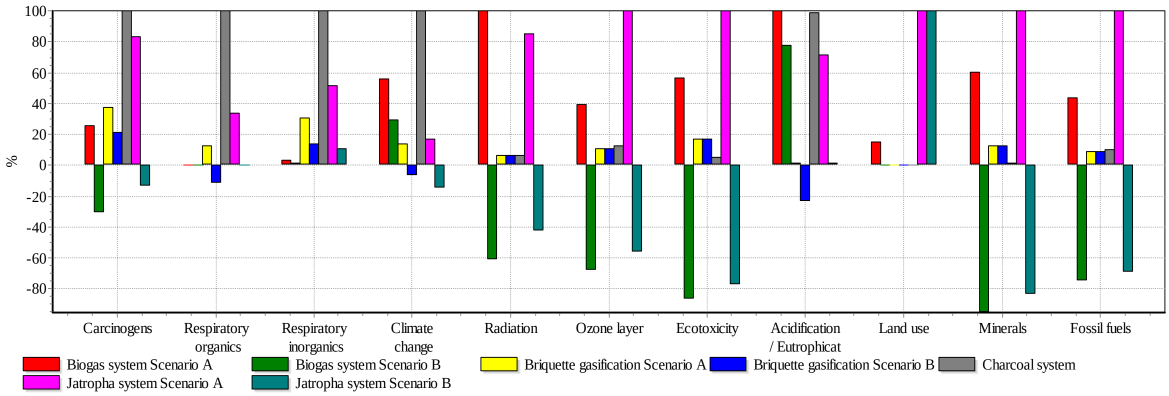


Figure 7.6. Relative environmental impacts of producing 1MJ of cooking energy from biogas, briquette gasification, and Jatropha systems under two scenarios compared to charcoal

7.5.2 Comparison of the single scores of environmental impacts under the two scenarios

Results of the single score environmental impacts per impact and damage categories are illustrated in Figure 7.7 (a) and (b), respectively. Significant reduction is observed in the land use impact category of scenario B of biogas system. This is probably explained by the reduction of allocation of impacts due to grass cultivation for biogas production. Briquette gasification system also showed a reduction in total environmental impact of about 50% compared to the first scenario. This is perhaps explained by decrease in impacts of respiratory inorganics. The reduction in levels of respiratory inorganics in this case is possibly attributed to avoided emissions during harvesting and pyrolysis of wood during charcoal production as a result of substitution with charcoal produced by the TLUD gasifier. Lastly, scenario B of the Jatropha oil system showed improved performance compared to scenario A. Most of the reduction is attributed to the respiratory inorganics impact category. This is most likely explained by avoided emission from open air burning of Jatropha seed husks. However, it can be observed from Figure 7.7 (b) that the most significant damage category of Jatropha system is on ecosystem quality, which is perhaps attributed to the land use impact category.

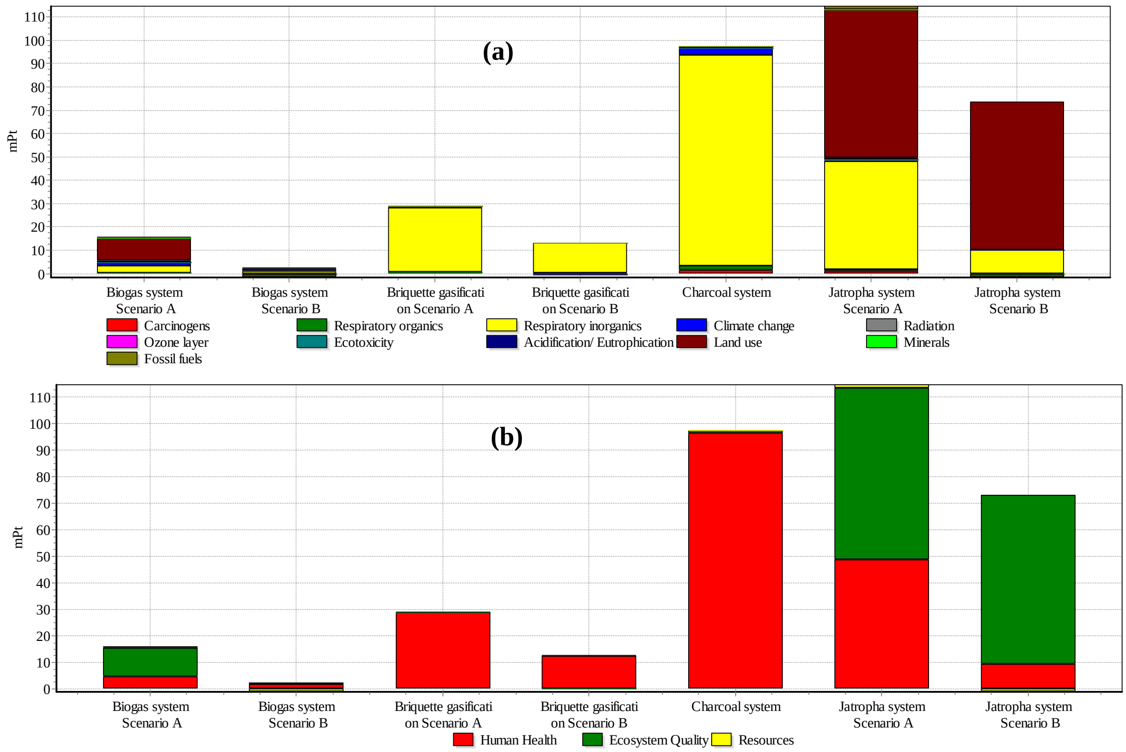


Figure 7.7. Comparison of single scores environmental impacts under two scenarios: (a) results with impact categories (b) results with damage categories

7.6 General discussions and limitations of the study

Results of this study showed that biogas system had the lowest environmental damage of the four energy systems studied. One main advantage of the biogas system observed in this study is the low level of respiratory inorganics impacts. This could be explained by lower levels of emissions such as particulates, SO_2 and NOx compared to the other three systems in this study. This therefore results in reduced damage to human health compared to charcoal, briquettes and Jatropha cooking. Similar findings were reported by other scholars (Afrane and Ntiamoah, 2011; Afrane and Ntiamoah, 2012). Damage to human health by indoor emissions due to use of solid fuels is one of the main causes of ill health and mortality in developing countries. This study suggests that biogas systems are a promising technology to combat this problem. Depending on assumptions concerning the system boundary and allocation, the land use impacts of biogas system due to grass production could increase significantly. Figure 7.8 shows that the total impacts of biogas system could increase from less than 5 mPt to almost 45 mPt if allocation of impacts of grass production to the system is increased from 0% to 20%. The 0% scenario corresponds to a situation where all environmental impacts due to grass production are attributed to dairy products. This therefore suggests that for reduced impacts of the biogas system, the productivity of the dairy enterprise must be maximised so that relative economic value of manure is low.

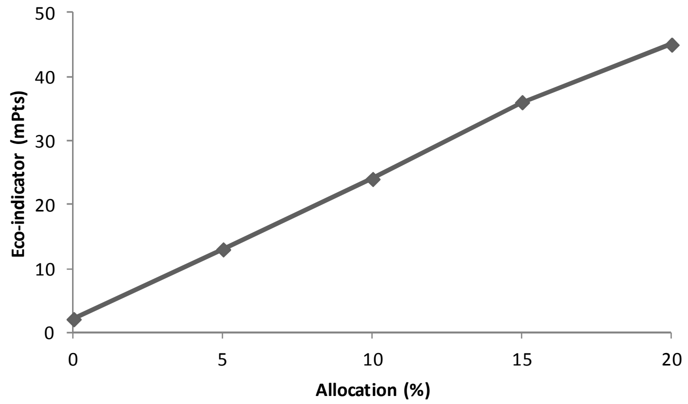


Figure 7.8. Effect of varying the allocation value to manure on the singe score of environmental damage by the biogas system

From the results of this study, it can be observed that the briquette gasification system has less environmental impacts compared to charcoal and Jatropha oil systems under both scenarios considered. One advantage of this system is the reduced impacts from respiratory inorganics during the use phase compared to when cooking with charcoal. This is due to the lower levels of particulates, SO_2 and NOx emissions from TLUD gasifier stoves compared to the latter systems. Generally, the total environmental damage by briquette gasification is less than both the charcoal and Jatropha systems. However, it is important to note that loss in soil quality due to collection of maize residues from fields was not considered in this study, since it was assumed to be waste. In reality, crop residues play important ecological functions such as reducing erosion and soil sealing, and ensures favourable biological activity of agricultural soils (Govaerts et al., 2008; Okello et al., 2013a). Collection of crop residues for energy application should therefore take into consideration the ecological importance of crop residues. Use of recoverability fraction could provide suitable guidelines on the quantity of residues that can be left in the fields. Several factors affect the recoverable fraction and actual fraction may vary from 19% to 75% (Cornelissen et al., 2012; Haberl et al., 2010).

Charcoal system showed the highest levels of respiratory inorganics compared to the other three technologies studied. This is perhaps explained by high levels of particulates, SO_2 and NOx emissions during all the unit processes of the charcoal system. Of concern is the emission in the indoor environment during cooking and charcoal so far has the highest indoor pollution impact compared to the other three technologies evaluated in this study. Efforts to improve the technology such as using better stove designs and charcoal making kilns could be beneficial to the environment.

Results of Jatropha plant oil cooking system showed that the land use impact category is the single most important contribution to environmental damage. Efforts aimed at reducing the land use impact of Jatropha can therefore be very beneficial to its environmental competiveness. This could be by growing Jatropha on degraded land, since the plant is known to have capacity to improve quality of degraded soils, with low water requirements. It is also known to offer benefits such as reducing soil erosion and improvement in soil properties (Ogunwole et al., 2008). Conversely, clearing forested lands for Jatropha production could greatly increase its impacts on ecosystem quality.

Alternatively, production of Jatropha in an agro-forestry system could be another plausible consideration, since the plant is known to intercrop well with a variety of agricultural, horticultural, silvicultural plants species (Iiyama et al.; Misra and Murthy, 2011). Some scholars have reported improved yields of food crops that have been intercropped with Jatropha (Makkar and Becker, 2009). The use of Jatropha as a support for vanilla plants has so far been reported in Uganda (Ejigu, 2008). The tree can also be used for fencing and land demarcation, while producing seeds as well, therefore reducing land requirements. Currently, Jatropha is not a well-understood plant and its yields are known to vary greatly under field conditions (Iiyama et al.). Improving yields through proper selection of planting materials or genetic improvement could result in reduced land requirements.

This study has also shown that proper handling and reuse of by-products of Jatropha processing like seed cake and husks can significantly reduce its environmental impacts. Use of seed cake as a fertilizer results in positive environmental impacts by reducing the use of mineral fertilizers, therefore improving the environmental competitiveness of the Jatropha energy system. Utilisation of seed husks as raw material for briquette production is also another possibility of reducing environmental damage of Jatropha plant oil system.

However, it should be noted that this study had some limitations. Firstly, there were limitations of data from the actual context of the study area. In most cases, the data used were from laboratory settings which might differ from the actual emissions under field conditions. However, effort was made to get representative data from other developing countries with similar technologies and socioeconomic settings to Uganda. The results of this study therefore present a fairly accurate perspective of the actual environmental impacts of the four technologies studied. Nevertheless, efforts to verify the findings of this study with data collected from the study area, preferably under field conditions could provide better insight into the environmental impacts of the technologies. The other important limitation is that social, economic and technical aspects of these technologies have not been considered in this study. It is important to holistically assess these aspects since they all have influence on the sustainability of bioenergy technologies. Future work could consider inclusion of these aspects to better assess the sustainability of each of the technology.

7.7 Conclusions

In this chapter, the environmental impacts of four energy systems for cooking were evaluated using the life cycle assessment methodology. Results show that biogas systems have the lowest environmental impact compared to Jatropha, briquettes and charcoal systems. However, with improved recycling, both briquette and Jatropha systems showed better environmental performance than charcoal. All the three technologies showed reduction in respiratory inorganics compared to charcoal. Their use could probably be an important means of reducing indoor air pollution, which is one of the major causes of ill health and premature death in many developing countries. Findings also showed the performance of Jatropha and biogas systems could be greatly improved through recycling of by-products to replace mineral fertilizers. In conclusion, use of Jatropha oil, biogas and briquette gasification in TLUD stoves as cooking fuels could result in improved environmental performance compared to charcoal.

Chapter 8 – Multi-criteria sustainability assessment of Ugandan bioenergy systems

Chapter 8 – Multi-criteria sustainability assessment of Ugandan bioenergy systems

Summary

Sustainable development aims at achieving social, economic, and environmental objectives simultaneously. These are conflicting objectives, for which multi-criteria analysis is well suited for their solution. In this chapter, sustainability of the biogas, briquettes, charcoal and Jatropha cooking energy systems were evaluated under Ugandan conditions. The study was based on multi-criteria decision analysis model using Preference Ranking and Organisational Method for Enrichment Evaluation (PROMETHEE) and Graphical Analysis for Interactive Aid (GAIA) methods. Under business as usual scenario, biogas and charcoal systems were found to be incomparable under the PROMETHEE I partial ranking scheme. Also, briquettes and Jatropha energy systems were incomparable. However, the PROMETHEE II complete ranking resulted in highest preference to biogas, followed by charcoal, while briquettes registered worst performance. In an alternative scenario with increased recycling of by-products as fertilizer, biogas system had the best sustainability ranking under PROMETHEE I partial ranking. This was followed by charcoal and Jatropha, which were incomparable and again the worst performer was the briquettes system. The PROMETHEE II complete ranking resulted in biogas as most sustainable, followed by Jatropha, charcoal and briquettes, respectively. The study therefore suggests that biogas is the most sustainable energy for household cooking in Uganda.

8.1 Introduction

One of the major challenges faced by developing countries today is provision cooking energy that is compatible to the socio-economic status of the population, technologically appropriate and environmentally friendly. Currently, majority of the urban population in sub-Saharan Africa (SSA) rely on charcoal as the dominant source of cooking energy (Kammen and Lew, 2005; Zulu and Richardson, 2013). The charcoal value chain is a major employer, with significant contribution to the rural economy of developing countries (Zulu and Richardson, 2013). The technology is simple, cheap, readily available, and easy to use as well as to replicate. However, its use is faced with challenges and uncertainties. For example, indoor air pollution from use of solid fuels is one of the major causes of health challenges in developing countries today. Use of charcoal is also blamed for its contribution to deforestation and forest degradation (Chidumayo and Gumbo, 2013), and its long term sustainability to meet growing demands remain uncertain (Mwampamba, 2007). Moreover, devices used for charcoal production and use are inefficient leading to wastage of biomass resources (Okello et al., 2013b).

Consequently, there are various efforts aimed at improving the efficiency of the charcoal production and combustion processes (Kshirsagar and Kalamkar, 2014). Other efforts aim at finding alternative technologies to replace or substitute charcoal. Domestic biogas system is one of the technologies being promoted for cooking in many developing countries. The model is based on cattle manure as substrate with the fixed dome bio-digester design as the most popular technology in SSA (Ghimire, 2013). Biogas systems provide several benefits including, reduction in indoor air pollution and deforestation. It is also a means of sanitising wastes such as cattle manure, while the slurry is a very good organic fertilizer. However, the technology is faced with challenges that limit its large scale adoption in developing countries. High investment cost and inadequacy of skilled personnel to provide technical support are examples of challenges limiting adoption of the technology (Surendra et al., 2014).

Briquetting of agricultural and forest residues is another technology that is also being promoted as an alternative to charcoal in Uganda (Mwampamba et al., 2013). Just like biogas, briquetting of biomass residues could play an important role in reducing deforestation rates in the country. However, technological barriers due to lack of skilled personnel and high investment costs, higher production costs of briquettes compared to wood and charcoal are some of the challenges to the technology (EEP, 2013). Combustion of briquettes could also lead to environmental challenges such as indoor air pollution and emissions of greenhouse gases. Low efficiencies of combustion appliances and emissions concerns are currently being addressed by the introduction of top-lit updraft (TLUD) gasifier stoves (Martin et al., 2013). The high initial investment and operating costs of briquetting system remains another major challenge to the dissemination of the technology in Uganda.

Recently, Jatropha plant oil is also being introduced as a possible fuel for direct use in cooking stoves and some engines powering multifunctional platforms to provide mechanical and electrical power in rural areas in Africa (Avinash et al., 2014; Eckart and Henshaw, 2012). Advantages of Jatropha as a bioenergy crop includes its ability to grow and even restore degraded land with minimum inputs of water and other crop production requirements. Jatropha is also known to have medicinal value and is one of the plants used in Uganda for indigenous livestock treatment (Nabukenya et al., 2014). However, it is a relatively new technology in Uganda and other developing countries. Its production might cause severe impact on crop production due to competition for resources for food production such as agricultural land and labour (Eckart and Henshaw, 2012). Being a new technology, it still faces challenges with limited acceptability, lack of skilled personnel and proven technologies for its use in Uganda (Okello et al., 2014).

With this background, it becomes apparent that the decision to select a suitable technology for use in developing countries is a very complex problem, since each technology has a number of benefits and challenges. Moreover, the right choice should ensure sustainability of energy supply for the current generation without compromising the needs of the future generation. Therefore, it becomes critical that suitable tools to aid decision making to ensure sustainable energy systems in developing countries are developed, and tested under such conditions. Currently, this remains a major challenge since there are generally limited examples of proven tools and methodologies to aid selection of sustainable choice of energy systems in developing countries.

The work presented in this chapter therefore aimed at developing a decision making methodology for selecting the most sustainable options amongst a finite set of bioenergy systems in developing countries. The method was developed based on Preference Ranking and Organisation Method for Enrichment Evaluation (PROMETHEE) and Graphical Analysis for Interactive Assistance (GAIA) and applied for ranking four bioenergy systems for cooking in Uganda.

The methodology used for sustainability assessment of bioenergy systems is based on multi-criteria decision analysis (MCDA). Specifically, this study employed the PROMETHEE and GAIA methods. The PROMETHEE methods provided ranking schemes while the GAIA tool was used for descriptive analysis of the MCDA problem. Analysis was carried out with the aid of Visual PROMETHEE 1.4 software (VP Solutions, 2013). Choice of the method was based on its ease of use due to its rather less complex algorithms compared to other MCDA methods (Pohekar and Ramachandran, 2004). The PROMETHEE methods belongs to the “French School” of MCDA methods and uses outranking principle to prioritise a finite set of alternative actions on the basis a given set of evaluation criteria (Løken, 2007).

8.2 The PROMETHEE methods

8.2.1. Alternatives, criteria evaluation and weights

Implementation of the PROMETHEE method requires that the set of actions to be ranked are well defined. A set of criteria suitable for evaluating all the alternatives is then defined. This is followed by an evaluation process where each alternative action is evaluated on the basis of the criteria. Since the criteria do not have equal importance, the decision maker is required to assign weights, w_j to all the criteria on the basis of their perceived relative importance.

8.2.2 Transformation of pairwise deviations using preference functions

Mathematically, a multi-criteria decision problem to be solved using the PROMETHEE method can be expressed using Equation 8.1 (Brans, 2002).

$$\max\{f_1(a), f_2(a), \cdots, f_j(a), \cdots, f_k(a) | a \in A\} \qquad (8.1)$$

where, A is a set of n alternative actions to be ranked on the basis of k evaluation criteria: $f_1(\cdot)$, $f_2(\cdot)$, …, $f_j(\cdot)$, …, $f_k(\cdot)$. Parameters $f_j(a)$ is the evaluation or score of action, a based on criterion $f_j(\cdot)$.

For each criterion, a suitable preference function, which transforms the deviation between evaluations of paired actions into a degree of preference ranging in value from 0 to 1 should be defined (Behzadian et al., 2010). For a particular alternative, a preference value of 0 means that it has no preference at all, while a value of 1 translates to full preference. Each criterion is therefore associated with a particular preference function, which measures the perception of the decision-maker about the criterion. There are six types of preference functions given in Appendix B, Table B1 (Brans and Mareschal, 2005; Mateo, 2012), all of which are available in Visual PROMETHEE 1.4 software (VP Solutions, 2013) used in this study. This step can be presented mathematically by supposing a pair of actions a_1, $a_2 \in A$; the degree of preference for action a_1 over a_2 can be expressed using Equation 8.2.

$$P_j(a_1, a_2) = G_j\{f_j(a_1) - f_j(a_2)\} \qquad (8.2)$$

where, G_j is a non-decreasing function of the deviation d, between $f_j(a_1)$ and $f_j(a_2)$. The degree of preference for action a_1 over a_2 increases with increasing values of the deviation $[f_j(a_1) - f_j(a_2)]$. Therefore, the degree of preference function can be expressed using Equation 8.3.

$$P_j(a_1, a_2) = \begin{cases} 0, & if \quad f_j(a_1) \le f_j(a_2) \\ G_j\left[f_j(a_1) - f_j(a_2)\right] & if \;\; f_j(a_1) \ge f_j(a_2) \end{cases} \tag{8.3}$$

8.2.3 Calculation of the multi-criteria preference index

The multi-criteria preference index is used to determine the degree of preference of action a_1 over a_2 when all the criteria a considered simultaneously. It represents the overall preference of one action over another. Suppose a given criteria $f_j(\cdot)$, for j = 1, 2, …, k, is associated with weight w_j, then the multi-criteria preference index of action a_1 over a_2 is calculated using the weighted average of the degree of preference $\pi(a_1,a_2)$, given by Equation 8.4.

$$\pi(a_1, a_2) = \frac{\sum_{j=1}^{n} w_j(a_1, a_2)}{\sum_{j=1}^{n} w_j} \tag{8.4}$$

8.2.4 Calculation of outranking flow indices

Preference flow indices are the basis for ranking the actions using PROMETHEE I partial ranking and PROMETHEE II complete ranking. They measure the degree of dominance of a given alternative over all other alternatives. Each alternative can be associated with, the leaving or positive flow $\phi^+(a)$, the entering or negative flow $\phi^-(a)$, and the net flow $\phi(a)$ given by Equations 8.5, 8.6 and 8.7, respectively.

$$\phi^+(a) = \frac{1}{n-1}\sum_{x \in A} \pi(a, x) \tag{8.5}$$

$$\phi^-(a) = \frac{1}{n-1}\sum_{x \in A} \pi(x, a) \tag{8.6}$$

$$\phi(a) = \phi^+(\mathrm{a}) - \phi^-(a) \tag{8.7}$$

The leaving flow is a measure of dominance or outranking character of alternative, a, over all the other alternatives in set A. High values of the leaving flow indicates high preference for an alternative. Meanwhile, the entering flow measures the outranked character, or how much a given action is dominated by all others alternatives in the set A. Lower values of entering flows indicates higher preference of a given action over all other alternatives in the set A. Lastly, the net flow indicates the preference of a given action, with higher values implying greater preference for the action.

8.2.5 PROMETHEE I partial ranking of alternatives

The PROMETHEE I partial ranking results in outcomes with some actions may not be prioritised due to incompatibilities and indifferences. It utilises the positive and negative $\phi^{+}(a)$ flows. In PROMETHEE I partial ranking, action a_1 is preferred to a_2 if and only if it is preferred to a_2 for both preference flows. This can be expressed mathematically using Equation 8.8 (Sultana and Kumar, 2012).

$$a_1 P^I a_2 \ if: \begin{cases} either, & \phi(a_1) > \phi^{+}(a_2) \ and \ \phi^{-}(a_1) \leq \phi^{-}(a_1) \\ or, & \phi(a_1) \geq \phi^{+}(a_2) \ and \ \phi^{-}(a_1) < \phi^{-}(a_1) \end{cases} \tag{8.8}$$

where P^I means *is "preferred to"* in the relationship between action a_1 and a_2. Using PROMETHEE I partial ranking can result in indifference in ranking of alternatives. Indifferences are situations where both actions a_1 and a_2 have the same leaving and entering flows. Indifference between two actions a_1 and a_2 is denoted as a_1Ia_2, and is given by Equation 8.9

$$a_1 I a_2 \ if: \ \phi^{+}(a_1) = \phi^{+}(a_2) \ and \, \phi^{-}(a_1) = \phi^{-}(a_1) \tag{8.9}$$

Two actions are incomparable, a_1Ra_2, under the conditions given in Equation 8.10. Literally, an incomparable situation does not imply that two actions cannot be compared, but that it is difficult to perform the comparison and thus the decision maker has to be more critical in selecting the options.

$$a_1 R a_2 \ if: \begin{cases} either, & \phi^{+}(a_1) > \phi^{+}(a_2) \ and \ \phi^{-}(a_1) > \phi^{-}(a_1) \\ or, & \phi^{+}(a_1) < \phi^{+}(a_2) \ and \ \phi^{-}(a_1) < \phi^{-}(a_1) \end{cases} \tag{8.10}$$

8.2.6 PROMETHEE II complete ranking of alternatives

To evaluate the complete ranking of alternatives, PROMETHEE II complete ranking is used. In this case, evaluation is based on the net flow, $\phi(a)$, according to Equation 8.11.

$$\begin{cases} a_1 \text{ is preferred to } a_2 \text{ if } \phi(a_1) > \phi(a_2) \\ a_2 \text{ is indifferent to } a_2 \text{ if } \phi(a_1) = \phi(a_2) \end{cases} \tag{8.11}$$

The disadvantage of PROMETHEE II is that information such as indifference and incomparability may be lost during the analysis process. Consequently, both PROMETHEE I partial ranking and PROMETHEE II complete ranking are used to evaluate alternatives actions.

8.2.7 Geometric Analysis for Interactive Aid (GAIA)

Geometric Analysis for Interactive Aid (GAIA) is a descriptive tool that facilitates graphical presentation of PROMETHEE analysis results. The GAIA analysis is based on the calculation of the single criterion net flow, $\phi(a)$, (Brans and Mareschal, 2005). The single criterion net flow for criteria $f_j(\cdot)$ is obtained by formulating net flow given in Equation 8.7 into the form in Equation 8.12.

$$\phi(a) = \frac{1}{A-1} \sum_{x \in A} w_j \phi_j(a) \tag{8.12}$$

where,

$$\phi_j(a) = \frac{1}{n-1} \sum_{b \neq a} \left[P_j(a,b) - P_j(b,a) \right] \tag{8.13}$$

The single criterion net flow always range from the worst to the best possible values of -1 and +1 , respectively. It is the net flow obtained when all the weight is allocated to only one criterion $f_j(\cdot)$. It measures the degree by which alternative a, is outranking (if $\phi(a)>0$) or outranked (if $\phi(a)<0$), by all other alternatives on the basis of criterion $f_j(\cdot)$.

The single criterion net flow facilitates analysis of relative performance of an action on any criterion, and makes it possible to present the multi-criteria table in a k-dimensional space while considering criteria scales and preference functions used (VP Solutions, 2013). Due to difficulty in visualising the k-dimensional space, dimensional reduction using principle compliment analysis (PCA) is used to present the results in a series of orthogonal *two*-dimensional presentation, called GAIA plane, while retaining most of the information in the *k*-dimensional space (Ishizaka and Nemery, 2011).

8.3 Implementation of PROMETHEE to rank bioenergy technologies

8.3.1 Goal and objectives

The goal of this study was to promote the use of sustainable bioenergy technologies for cooking in Uganda, by improving the decision making process. Objective was to identify the most sustainable of biogas, briquettes, charcoal and Jatropha bioenergy technologies used cooking in Uganda. This is by ensuring that the technologies are socially acceptable, economically feasible, environmentally friendly and technologically practical. In reality, these conditions are conflicting and therefore a MCDA approach is best suited for its solution.

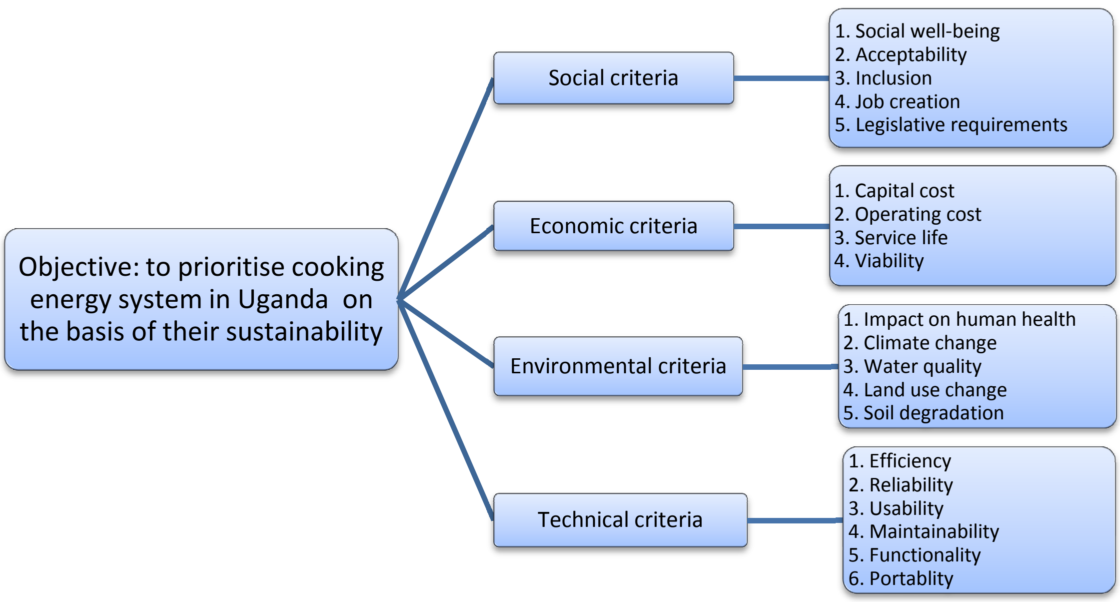


Figure 8.1. Decision hierarchy of MCDA ranking of Ugandan bioenergy technologies

8.3.2 Decision hierarchy

The decision problem was structured into a decision hierarchy given in Figure 8.1. To achieve the objective of identifying the most sustainable technology, the problem was decomposed into the social, economic, environmental and technical dimensions (Brans, 2002) of sustainability. For each dimension, a set of criteria were identified as illustrated in Figure 8.1.

8.3.3 Description of alternatives

A brief description of each technology is given here; more detailed description is given in Section 5.4 of this thesis, and in Okello et al., (2014). Biogas system involves cultivation of grass for feeding cattle and using the manure generated for producing biogas in fixed-dome bio-digester. The biogas is then conveyed in pipes to combustion devices and directly used for cooking. Briquette gasification system involves collection of maize residues and processing it into briquettes. Briquettes are used for cooking in TLUD gasifier stove, which is a micro-gasifier designed for cooking in developing countries. Charcoal is the traditional system, mainly produced from harvested natural forest vegetation in traditional earth-mound kilns. It is directly used in charcoal stoves; in this case *Kenya ceramic jiko* (KCJ) stove was considered. Lastly the Jatropha system involves cultivation of Jatropha plant, which produces Jatropha seeds from which oil is extracted, filtered and directly used for cooking. Background information on the status of these technologies in Uganda is available in Section 3.2 and Okello et al., (2013b).

8.3.4 Selection and weighting of criteria

The criteria were selected to ensure that they are suitable for the assessment of the sustainability of four energy systems. Selection of criteria was based on literature survey, followed by validation by a panel of multi-stakeholder. Weights were assigned to each criteria using analytical hierarchy process (AHP). Detailed description of the process of selecting and weighting criteria are given in Chapter 6 of this thesis.

8.3.5 Evaluation of social criteria

Social criteria were evaluated and results given in Table 8.1. Criterion job-creation was evaluated basing on the potential number jobs created along the supply chain of each technology. Only direct employment was considered in this study, since it was difficult to estimate number of indirect employment. Evaluation of the other four criteria were based on expert judgement and measured on a qualitative scale ranging from 1 to 5. In each case, 1, 2, 3, 4 and 5 means the evaluation of a given criterion on the scale was *very bad*, *bad*, *average*, *good* and *very good*, respectively.

Table 8.1. Evaluation results of social criteria

Alternative	Social criteria				
	Well-being	**Acceptability**	**Inclusion**	**Job creation**	**Legislations**
Biogas system	5	4	5	4	5
Briquette gasification	4	3	4	5	3
Charcoal	4	5	4	2	1
Jatropha oil	4	3	3	5	3

8.3.6 Evaluation of economic criteria

Evaluation of economic criteria was based on prevailing capital and operating cost for each technology supply chain. Detailed cost based on present market rates and assumptions for calculation of the internal rate of return (IRR) are given in Appendix C. Service life was estimated on the basis of number of years required to replace the technology, when it is no longer of any economic value. Each technology was assumed to have zero salvage value at the end of its service life. For the case of biogas, allocation of grass production cost of 10% was assigned to biogas, while 90% was to dairy products. Viability was evaluated using the internal rate of return (IRR) over an investment period of 15 years.

Table 8.2. Evaluation of economic criteria

Alternative	Economic criteria			
	Capital costs (USD)	**Operating costs (USD)**	**Service life (years)**	**Viability (IRR) (%)**
Biogas system	1278	379	15	22
Briquette gasification	6248	8505	10	15
Charcoal	157	9641	10	520
Jatropha oil	5641	1164	25	1

8.3.7 Environmental criteria

Environmental criteria were evaluated using life cycle assessment (LCA) methodology. Comparative LCA methodology was applied using ReCiPe endpoint and Eco-indicator 99 life cycle impact assessment (LCIA) methods, with a functional unit of 1 MJ of cooking energy. Life cycle inventory data used for the LCA is presented in Section 7.3 of this thesis. Climate change and land use were evaluated using the Eco-indicator 99 impact assessment method, using SimaPro 7.3 LCA software. Impacts on human health, water quality and soil degradation were evaluated using human toxicity, freshwater ecotoxicity and terrestrial ecotoxicity, respectively. The ReCiPe endpoint impact assessment method was used to evaluate the freshwater ecotoxicity and terrestrial ecotoxicity. Results of the evaluation, measured in eco-points are given in Table 8.3. Loss of biodiversity was excluded from the evaluation since there was no suitable method for assessing it in the LCIA methods employed in this study.

Table 8.3. Evaluation of environmental criteria

Alternative	Environmental criteria				
	Human health	Climate change	Water quality	Land use change	Soil degradation
Biogas system	2.62	5.36	89.10	19.03	6.31
Briquette gasification	0.47	1.34	10.90	0.01	4.79
Charcoal	0.12	9.56	4.20	0.01	1.60
Jatropha oil	3.63	1.34	11.30	127.56	13.40

8.3.8 Technical criteria

Six technical criteria presented in Table 8.4 were evaluated and included for the multi-criteria sustainability analysis. Currently, there are no generally accepted set of technical criteria and evaluation method for sustainability assessment of bioenergy technologies. The choice of the criteria used here was based on available literature and validation by a multi-stakeholder panel. Detailed explanations of the technical criteria are given in Table 6.4. Efficiency of the combustion appliance, given in Section 7.3, was used as the efficiency criteria. Criteria reliability and maintainability could be calculated using principles of reliability engineering as explained by Eti et al., (2007), and Sharma and Kumar (2008). However, due to lack of the relevant technical performance data of each of the bioenergy technology, they were evaluated by expert judgement on a five-point qualitative scale.

Table 8.4. Evaluation of technical criteria

Alternative system	Technical criteria					
	Efficiency	Reliability	Usability	Maintainability	Functionality	Portability
Biogas	55	4	4	4	4	2
Briquette	30	2	4	3	3	4
Charcoal	15	5	5	5	5	5
Jatropha oil	40	4	3	3	3	3

8.3.9 Choice of preference function and thresholds

The visual PROMETHEE 1.4 software assistant was used to aid selection of preference functions. This was supplemented by guidance from Podvezko and Podviezko (2010). Generally, the V-shape and Linear preference functions are best suited for quantitative criteria, the only difference between them being the threshold values. Meanwhile the Usual and Level preference functions are mainly used for quantitative criteria, while the Gaussian type is rarely used due to difficulty in parameterisation (Sultana and Kumar, 2012; VP Solutions, 2013). Similarly, the thresholds of preferences and indifferences were also selected by the author with the aid of the visual PROMETHEE software assistant. A complete list of preference functions, indifference and preference thresholds used in this study is given in Table 8.5. The table also provides the choice of objective functions, data type, and the weight of each criterion as assigned by a multi-stakeholder panel. However, it should be noted that since criterion loss of biodiversity was not included in this analysis, its weight was distributed to the other environmental criteria to ensure that their total equals to unity.

Table 8.5. Parameters for preference modelling

Parameters	Social criteria				
	Well-being	**Acceptability**	**Inclusion**	**Job creation**	**Legislations**
Unit	5-point	5-point	5-point	Number	5-point
Objective function	Maximise	Maximise	Maximise	Maximise	Maximise
Data type	Qualitative	Qualitative	Qualitative	Quantitative	Qualitative
Weight (%)	5.7	5.2	4.9	4.7	4.7
Preference function	Level	Level	Level	V-shape	Level
Indifference threshold (*q*) [a]	0.5	0.69	0.58	n/a	0.75
Preference threshold (*p*)[a]	1.0	1.85	1.58	4	2.41

Table 8.5 continued…

Parameters	Economic criteria			
	Capital cost	**Operating cost**	**Service life**	**Viability**
Unit	USD	USD	Years	%
Objective function	Minimise	Minimise	Maximise	Maximise
Data type	Quantitative	Quantitative	Quantitative	Quantitative
Weight	11.0	9.5	8.2	6.4
Preference function	V-shape	V-shape	V-shape	Linear
Preference threshold (*p*) [a]	n/a	n/a	n/a	10
Indifference threshold (*q*) [a]	5899.41	9362	14	507

Table 8.5 continued…

Parameters	Environmental criteria				
	Human health	Climate change	Water quality	Land use change	Soil degradation
Unit	Eco-points	Eco-points	Eco-points	Eco-points	Eco-points
Objective function	Minimise	Minimise	Minimise	Minimise	Minimise
Data type	Quantitative	Quantitative	Quantitative	Quantitative	Quantitative
Weight	6.6	4.7	4.1	3.6	2.9
Preference function	Linear	V-shape	Linear	Linear	Linear
Preference threshold (p) [a]	1.12	n/a	39.92	54.89	3.44
Indifference threshold (q) [a]	3.23	7.6	80.43	121.88	9.60

Table 8.5 continued…

Parameters	Technical criteria					
	Efficiency	Reliability	Usability	Maintainability	Functionality	Portability
Unit	%	5-point	5-point	5-point	5-point	5-point
Objective function	Maximise	Maximise	Maximise	Maximise	Maximise	Maximise
Data type	Quantitative	Qualitative	Qualitative	Qualitative	Qualitative	Qualitative
Weight	3.8	3.4	3.2	3.0	2.8	1.5
Preference function	V-shape	Linear	Linear	Linear	Linear	Linear
Preference threshold (p) [a]	n/a	0.75	0.69	1.00	0.69	0.75
Indifference threshold (q) [a]	31.53	2.41	1.85	2.00	1.85	2.41

[a] Please refer to Table B1 for explanation

8.4 Results and discussions

8.4.1 PROMETHEE ranking

The leaving $\phi^+(a)$, entering $\phi^-(a)$, and net $\phi(a)$ flows are the basis of PROMETHEE ranking schemes. These were evaluated using the Visual PROMETHEE version 1.4 software and results are presented in Table 8.6.

Table 8.6. PROMETHEE flow table for the energy systems

Energy system	Leaving flow $\phi^+(a)$	Entering flow $\phi^-(a)$	Net flow $\phi(a)$
Biogas (a_1)	0.3739	0.1829	0.1910
Briquettes (a_2)	0.1398	0.3304	-0.1906
Charcoal (a_3)	0.3795	0.2715	0.1080
Jatropha (a_4)	0.2259	0.3344	-0.1084

Evaluation of PROMETHEE II complete ranking can be directly obtained from the net flows $\phi(a)$ given in the Table 8.6. The higher the flow value, the better the rank of the technology, meaning that biogas had the best rank, followed by charcoal, Jatropha and briquettes, respectively. Also, the flow results given here provide information used for PROMETHEE I partial ranking. The visual PROMETHEE software tool provides a variety of graphical schemes for visualisation of the results presented in the following sections.

8.4.2 PROMETHEE I partial ranking

PROMETHEE I partial is obtained by comparing the leaving flows, $\phi^{+}(a)$, and the entering flows, $\phi^{-}(a)$, given in Table 8.6. Results of the PROMETHEE I partial ranking for this study is given in Figure 8.2. The left axis of the figure gives the ranking of the energy systems based on the leaving flow $\phi^{+}(a)$, while the right axis gives ranks on the basis of entering flows $\phi^{-}(a)$.

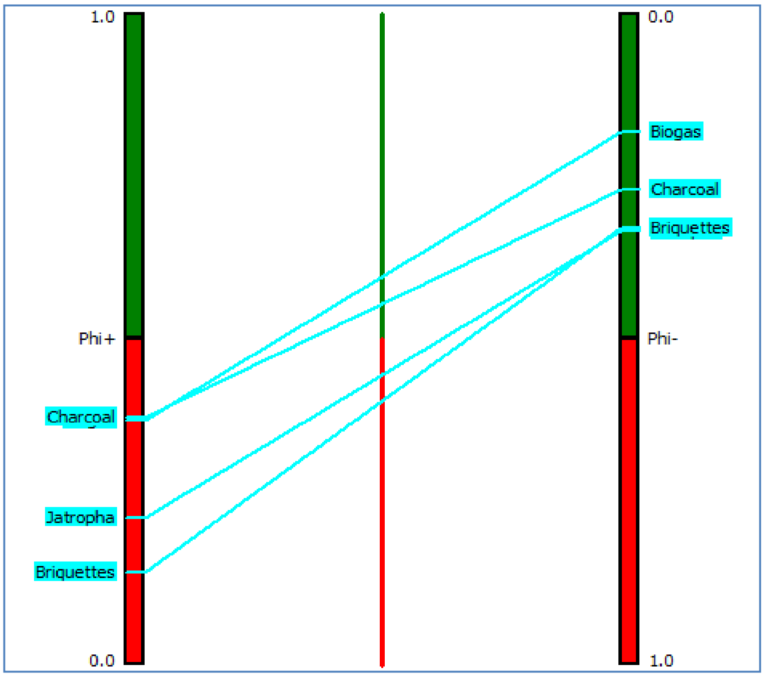


Figure 8.2. Graph showing results of PROMETHEE I partial ranking

Figure 8.2 shows that charcoal and biogas alternatives are generally better than the briquette and Jatropha systems since they are on top of the chart. However, the lines joining the ranks of the biogas and charcoal on the left and right axes cross each other. This means that the two alternatives are incomparable. Similarly, it can be observed that briquettes and Jatropha systems are also incomparable. Incomparability does not necessarily mean that the two actions cannot be compared, but that the two choices are difficult for the decision maker to select. It is a situation corresponding to lack of consensus to declare that one action is clearly better than the other (Brans, 2002). The intersection of lines joining the alternatives and green-red line between the left and the right axes in Figure 8.2 corresponds to the net flow, $\phi(a)$ scores.

8.4.3 PROMETHEE II Complete ranking

The net flows given in Table 8.6 are the basis for PROMETHEE II complete ranking. Results of the PROMETHEE II complete ranking was presented graphically by indicating the net flows along a vertical axis as shown in Figure 8.3. Location of the alternatives on the axis indicates their ranks under PROMETHEE II complete ranking scheme. Best alternatives are usually at the top while the worst are located at the bottom of the axis. Results shown in Figure 8.3 suggest that the biogas energy system ranked as the best alternative, followed by charcoal system. Briquette system on the other hand had the worst overall score, meaning that it is the least preferred option.

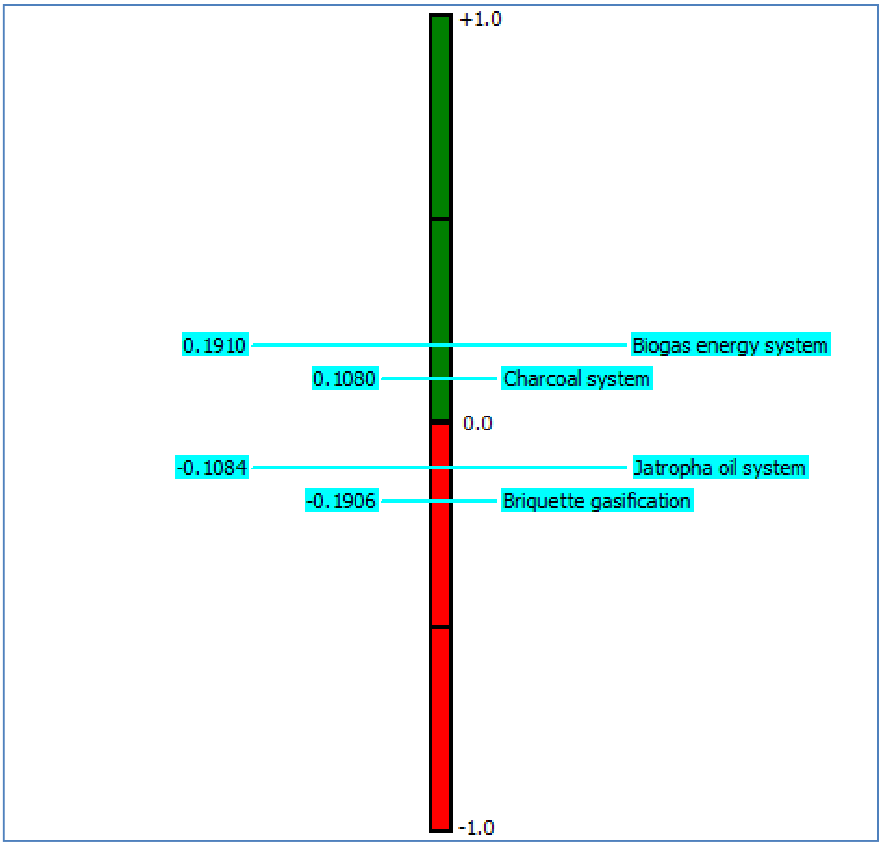


Figure 8.3. Graph showing results of PROMETHEE II complete ranking

Unlike PROMETHEE I ranking where incomparability and indifference can be detected, this information is lost under PROMETHHEE II complete ranking. The PROMETHEE diamond given in Figure 8.4 therefore provides a useful tool for visualising results of both ranking schemes. It has a 45° oriented square which provides information on the entering and leaving flows. The vertical axis along the diagonal of the square gives the net flows. Cones are drawn for each alternative from the left of the plane and used for visualising results of PROMETHEE I partial ranking. Cones that overlap others correspond to preferred alternatives. Pairs of cones that intersect each other indicate conditions of incomparability. Results of this analysis further confirm that charcoal and biogas systems are incomparable alternatives, just like briquettes and Jatropha systems. The net flows further confirm the results of PROMETHEE II complete ranking, with biogas as the best and briquette as the worst alternatives.

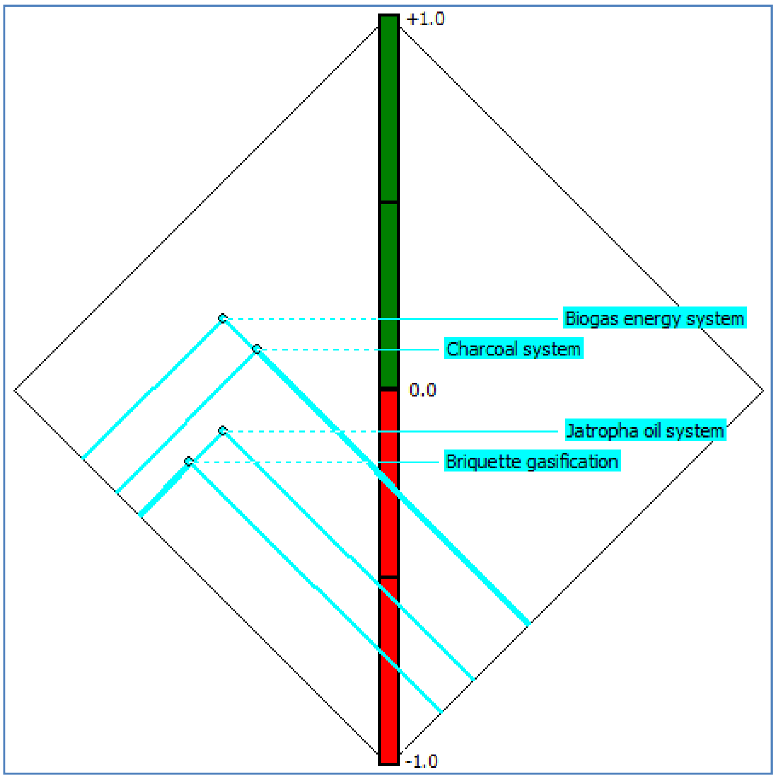


Figure 8.4. Graph showing result of PROMETHEE I and II ranking

8.4.4 Results of GAIA Analysis

The GAIA plane for the present study is given in Figure 8.5 (a) and (b). The purpose of GAIA analysis is to illustrate the global performance of actions in relation to the evaluation criteria as well as the relationships between criteria. Each criterion is presented on the plane using an axis, while actions are displayed as points. The GAIA plane in Figure 8.5 was obtained by converting the representation of the 20-dimensional planes of criteria into a two-dimensional plane using PCA, while maintaining the maximum possible amount of the original information. However, during PCA, some of the original information is lost (Dağdeviren, 2008). Quality value given in the GAIA plane is an indication of the amount of information retained during PCA transformation; in this case, 86% of the original information of criteria is retained while 14% is lost.

The GAIA plane provides plenty of useful information for decision making while ranking alternative actions. For example, criteria of similar preferences are oriented in the same direction on the GAIA plane. In this study, it can be observed that efficiency, operations costs and social wellbeing, have similar preferences. Other examples of criteria with similar preferences are soil degradation, land use change, and capital costs. The GAIA plane also helps in identifying conflicting criteria, since they are oriented in opposite directions on the plane. The pairs portability and efficiency; social wellbeing and impact on water quality are typical examples of conflicting criteria in this study.

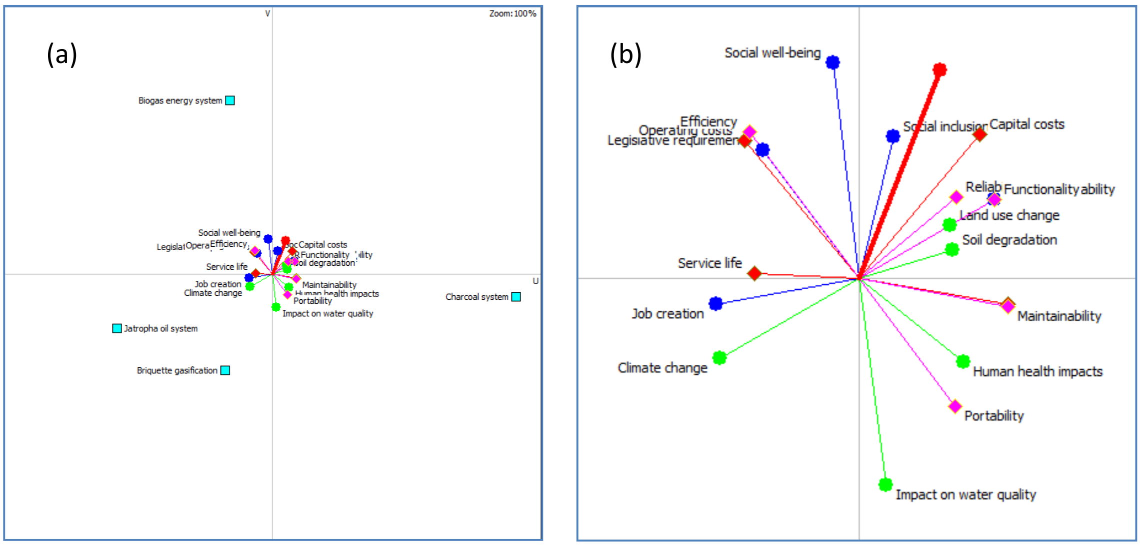


Figure 8.5. GAIA plane for the bioenergy systems at 86% quality; (a) - plane at 100% zoom level; (b) - plane at 400% zoom

Additional information such as performance of the alternatives in relation to each other can also be figured out from the GAIA plane. Similar alternatives are usually displayed close to each other on the plane; in this case, Jatropha and briquette systems are quite similar. On the other hand charcoal and biogas are quite different actions from each other, as well as from Jatropha and briquette systems.

Another important feature on the GAIA plane is the decision axis, which is given by the thick red line, shown at higher magnification in Figure 8.5 (b) for better visualisation. The decision axis is the weighted average of the criteria axes. It represents the suggested direction of the action which the decision maker has to take (Albadvi et al., 2007; Wang and Yang, 2007); in this case, the biogas system, since it is the closest in direction to the axis. The axis is useful for identifying criteria which have high influence on PROMETHEE II ranking. In this case, it can be observed that social well-being, social inclusion, capital costs and functionality criteria highly influence the final results since they are close to the axis. Criteria like impact on water quality and job creation are oriented in the opposite direction to the decision axis, meaning they are given lower weights. Changing the weights of criteria usually results in a shift in the position of the decision axis.

The orientation of the criteria axis on the GAIA plane provides useful information about the relationship between criteria and alternatives. Criteria are usually oriented towards the direction of the alternative for which it is favourably evaluated. For example, the criterion maintainability is oriented to the right of the GAIA plane, where the charcoal alternative is located. This implies that charcoal system has a favourable maintainability attributes, unlike for example, Jatropha, which is in the opposite direction. Better visualisation can be obtained when the criteria axis is included in the GAIA plane as shown in Figure 8.6. Moving from the right to the left of the GAIA plane, charcoal ease of maintenance is followed by briquettes, biogas and worst performer is Jatropha system. Similar analysis can be performed for all the criteria.

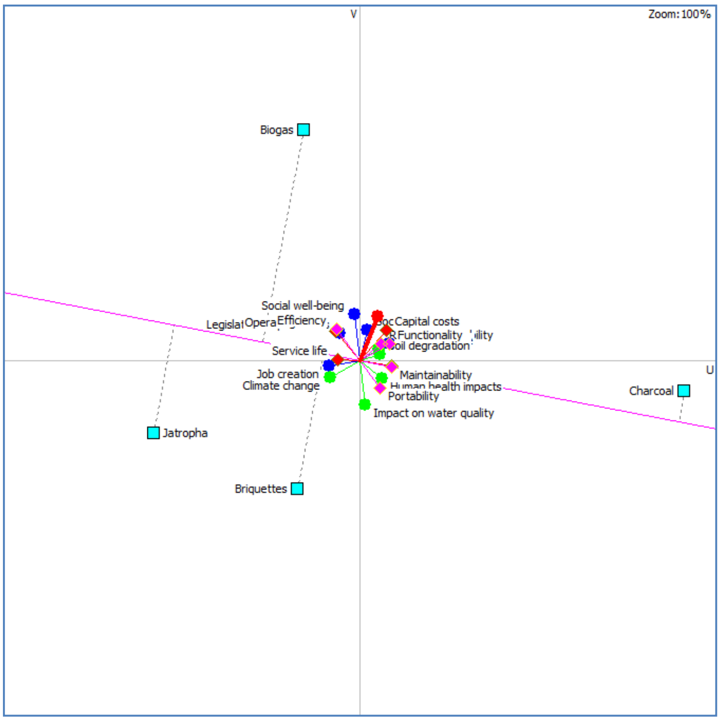


Figure 8.6. GAIA plane showing the axis of the maintainability criteria

8.4.5 Sensitivity analysis

Sensitivity analysis was carried out to determine the effect of varying the weights of the criteria on the ranking of the alternatives. Stability intervals of weights of criteria were calculated and presented in Table 8.7. This represented the range within which the ranks of the alternatives do not change under the PROMETHEE II complete ranking schemes. The results showed that social wellbeing has a stability interval from 0% to 100%, meaning that the ranks of the alternatives are not sensitive to changes in weight of this criterion. However, criteria portability, maintainability, soil degradation, land use change, and impact on water resources showed relatively small stability interval. This implies that the ranks of the alternatives are highly sensitive to changes in weight of these criteria.

Table 8.7. Stability interval for criteria weights

Criteria	Weight	Weight stability interval (%)	
		Minimum	Maximum
Social wellbeing	5.70	0.00	100.00
Social acceptability	5.20	0.00	15.70
Social inclusion	4.90	0.00	15.34
Job creation	4.70	0.00	18.01
Legislative requirements	4.70	0.00	24.35
Capital costs	11.00	0.00	33.71
Operating costs	9.50	3.43	23.27
Service life	8.20	2.29	20.83
Viability	6.40	0.00	11.98
Human health impacts	6.60	0.00	12.88
Climate change	4.70	0.00	17.79
Impact on water	4.10	0.00	9.88
Land use change	3.60	0.00	9.48
Soil degradation	2.90	0.00	9.71
Efficiency	3.80	0.00	21.39
Reliability	3.40	0.00	17.16
Usability	3.20	0.00	13.92
Maintainability	3.00	0.00	8.69
Functionality	2.80	0.00	13.57
Portability	1.50	0.00	7.28

The charts of visual stability interval given in Figure 8.7, perhaps give a more intuitive presentation of the variation of PROMETHEE II complete ranking with changes in weights of criteria. The horizontal axis of the chart gives the weight of the criterion under consideration. Net flows are given by the vertical axes of the chart. Lines representing variation in net flows for a given alternative are drawn joining the scores at 0% and 100% on the left and right axes, respectively. Preference flow corresponding to the left of the chart represents a situation in which weight of 0% is assigned to criterion. It corresponds to a situation where the criterion does not have any contribution to the overall ranking of the alternatives. The axis on the right-hand side of the chart represents a situation where criterion under consideration is assigned a weight of 100%, implying that ranking is based only on the criterion.

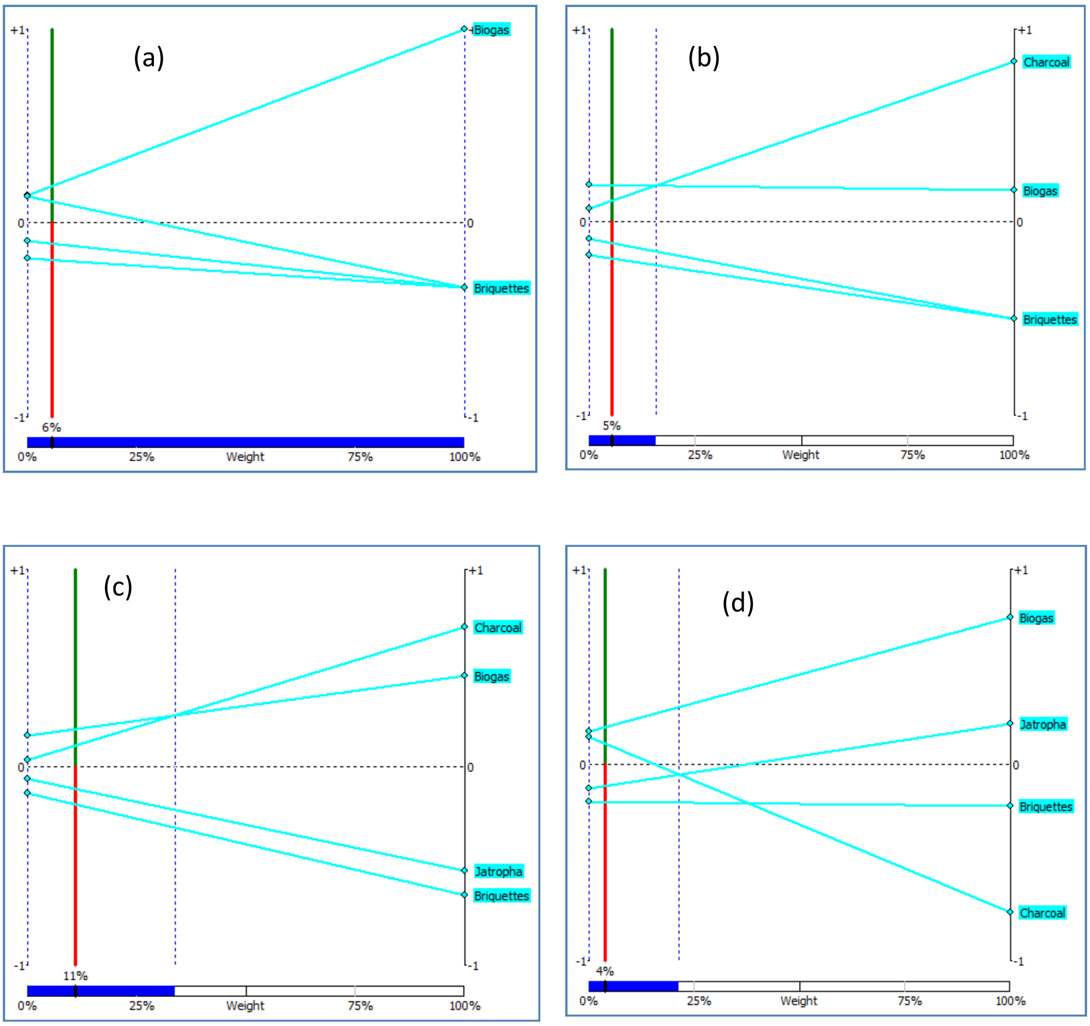


Figure 8.7. Visual stability interval (a) social well-being, WSI = 0 to 100%, (b) acceptability WSI = 0 to 15.7% (c) capital costs, WSI = 0 to 34% (d) efficiency, SI = 0 to 21%

The inclination of the line provides information on the evaluation of the criteria. For example, in Figure 8.7 (a), it can be noted that biogas performs very well on the social wellbeing criterion, since its net flow increases with increasing values of the weight of the criterion. However, briquettes, charcoal and Jatropha exhibit poor performance on the social wellbeing criterion due to the decreasing net flow with increase in the weight of the criterion. Following similar arguments, sub-figures 8.7 (b), (c) and (d) can be interpreted to provide more insight into the stability of the ranking of the alternatives with variation in weight of the criteria. Stability interval is plotted with dotted vertical lines on the chart. It can be observed that the ranks are more sensitive to the social acceptability criterion

(Figure 8.7 (b)), and not sensitive to the social wellbeing criterion (Figure 8.7 (a)). Analysis of stability interval illustrated here can be extended to all the remaining 16 criteria used in this study.

Quite often, it is of interest to the decision maker to evaluate the sensitivity to the ranking of the alternatives when the weights of criteria are all set to an equal value that is 5% for each of the 20 criteria in this study. Assumption of equal weight of criteria was evaluated and results presented in Figure 8.8 (b). When compared to the initial case when weight of criteria were assigned by a multi-stakeholder panel, it can be observed that results of PROMETHEE II complete ranking of biogas and charcoal, shown by the upper half of the chart, get inverted when weights of criteria are equal. Similarly, rank inversion is observed between Jatropha and briquette energy systems. However, overall, briquettes and Jatropha energy systems ranked lower than charcoal and biogas systems under both sets of criteria weights.

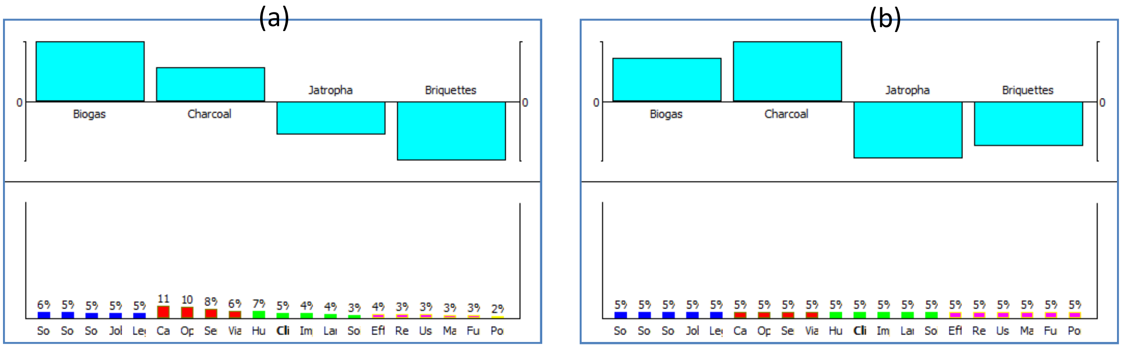


Figure 8.8. Effect of changing criteria weight on ranking (a) weights at initial conditions, (b) all criteria set to have equal weights.

8.5 Scenario analysis

A scenario was developed assuming increased recycling of by-products of biogas and Jatropha energy systems as described in Section 7.5 of Chapter 7. Results of LCA using ReCiPe endpoint analyses were used to estimate impacts on human health, climate change, water quality and soil degradation. It was also hypothesised that through training, the social acceptability of Jatropha and briquettes can be improved from average to good on the five-point qualitative scale. These values were used to develop a new scenario and was analysed using the visual PROMETHEE software. Corresponding preference functions and threshold values were also adjusted to suit the new data set indicated in

Table 8.8. Other variables of the remaining criteria were kept the same as in the business as usual scenario.

Table 8.8. Parameters and evaluations for the alternative scenario

Parameters	Environmental criteria				
	Social acceptability	Human health	Climate change	Water quality	Soil degradation
Unit	5-point	Eco-points	Eco-points	Eco-points	Eco-points
Objective function	Maximise	Minimise	Minimise	Minimise	Minimise
Data type	Qualitative	Quantitative	Quantitative	Quantitative	Quantitative
Weight (%)	5.2	6.6	4.7	4.1	2.9
Preference function	Level	Linear	Linear	Linear	Linear
Preference threshold (p) [a]	0.5	43.70	50.37	65.51	9.36
Indifference threshold (q) [a]	1.0	121.07	127.07	184.82	26.88
Evaluations					
Biogas	4	-109.10	8.41	-188.80	-19.21
Briquettes	4	15.77	-10.57	14.25	9.58
Charcoal	5	4.00	112.15	4.85	3.20
Jatropha	4	-85.58	-28.92	-104.4	-15.54

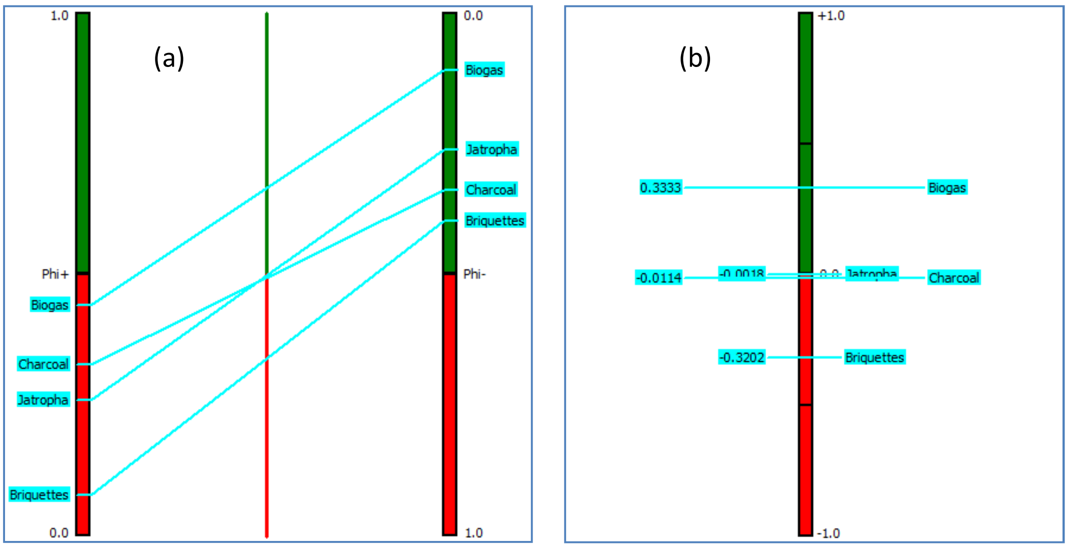


Figure 8.9. PROMETHEE ranking in scenario with improved recycling of wastes (a) PROMETHEE I partial ranking, (b) PROMETHEE II complete ranking.

Results of this new scenario are given in Figure 8.9. The PROMETHEE I partial ranking given in Figure 8.9 (a) demonstrates that biogas energy system is the most sustainable overall, since it is above all the other energy systems. The Jatropha system showed a general upward shift on the chart, meaning there is an improvement in its sustainability. However, it can be observed that Jatropha and charcoal system are incomparable under this scenario. Briquettes system generally ranked lowest under PROMETHEE I partial ranking scheme. Figure 8.9 (b) is an illustration of the PROMETHEE II complete ranking, from which it can be deduced that biogas system ranked the best followed by Jatropha system, and briquettes system ranked worst overall.

8.6 General discussions proposal for future research

In this chapter, the sustainability of four energy systems used for cooking in Uganda was assessed on the basis of 20 criteria using MCDA. The criteria were classified under the social, economic, environmental and technical themes of sustainability. Currently, there are no generally accepted lists of criteria for assessing bioenergy systems, and those used in this study were developed by a team of experts and multi-stakeholder panel. Environmental and economic criteria were evaluated using quantitative methods. The LCA methods and generally accepted for evaluating environmental impacts of products and services into quantifiable results. Also there are a number of financial methods that can be used to quantify the economic criteria. However, most of the social and economic criteria could not be quantified and their evaluations were based on a five-point qualitative scale. Evaluation of social and technical criteria used here was therefore quite subjective and therefore may not be accurate and repeatable depending on the judgement of the decision maker. This could have impacts on the overall results of the ranking. Future research could consider development of quantifiable set of technical and social criteria.

In this study, evaluation of economic and environmental criteria was restricted to a radius of 40 km between the point of material collection and use. However, in practice, biomass material can be transported over much longer distances. This could result in increased operating costs and environmental load due to transportation. It is expected that results of this study could be affected by this. When analysing the environmental performance of charcoal, the impact on biodiversity were not taken into consideration due to limitations of appropriate methods. Wood harvested for charcoal in developing countries is mainly of indigenous species, that play important ecological, economic as well as having medicinal values. These were not evaluated in this study meaning that the results presented could have over-estimated the actual sustainability of the charcoal energy system. It is quite complex to model all the environmental impacts of a product, nevertheless, future effort could consider improving the accuracy of quantification of the criteria. Also possibility of producing charcoal from dedicated short rotation forestry could be evaluated, since there are currently uncertainties about long term sustainability of natural vegetation to meet increasing demand.

Briquette gasification system generally featured last in ranking under both scenarios considered in this study. Some of the contributing factors include high capital and operating costs. Possibility of utilising secondary residues to reduce collection costs is probably a useful strategy to improve the sustainability of the technology. These residues are produced in agro-processing plants such as maize and rice mills located in Gulu municipality. Quantification of the residues and evaluation of their sustainability in comparison with the other technologies could be a worthwhile effort. Other studies could aim at evaluating the impacts of intercropping on the sustainability of the Jatropha energy systems.

8.7 Conclusions

This study aimed at evaluating the sustainability of four bioenergy systems used in Uganda. The PROMETHEE and GAIA methods were used for ranking the technologies. Under business as usual scenario, biogas and charcoal were incomparable under PROMETHEE I partial ranking, while biogas was rated as the most sustainable option under complete ranking schemes. Recycling of by-products as fertilizer resulted in improved sustainability of biogas and jatropha systems. In conclusion, the study suggests that biogas is perhaps the most sustainable energy alternative for Uganda amongst the four systems considered in this study. Also, sustainability of both biogas and Jatropha significantly increase with recycling of by-products. The PROMETHEE and GAIA methods used in this study proved to be very promising tools to aid sustainable bioenergy decision making under developing country conditions. Future research could consider improving the accuracy of evaluation of social and technical criteria. Development of more detailed model simulating the actual situation as closely as possible could greatly improve the accuracy of the results.

Chapter 9 – Overview and conclusions

Chapter 9 – Overview and conclusions

Summary

This chapter aims at providing the main results of this study together with their implications. The chapter also provides a summary of the major limitations and challenges faced during the study along with proposal for future research. Conclusions drawn from the study are provided in the last part of the chapter.

9.1 Overview of key results and discussions

The advent of the concept of sustainability and need to attain sustainable development has created a major challenge to decision making in the recent past. Use of traditional biomass for cooking in developing countries is one of sectors facing urgent need for sustainable development. Therefore, this study was aimed at developing methodologies for improving the decision making process when selecting bioenergy technologies for cooking in developing countries. The proposed decision making framework integrates social, economic, environmental and technological concerns of sustainability using a MCDA methodology. Involvement of stakeholders during the decision making process was also taken into consideration. The conceptual framework of the methodology is presented in Chapter 4. This study provides a detailed application example of the methodology for analysing four alternative biomass energy systems under Ugandan conditions. The proposed method is quite generic and it is possibly applicable for assessing sustainability of cooking energy systems in developing countries with similar socio-economic and technological conditions as Uganda.

9.1.1 State of the art of bioenergy technologies

The proposed sustainability assessment methodology was designed and tested in Uganda as a representative developing country. Like in many other developing countries, there was very limited availability of background literature on the status of bioenergy technologies in the country. Chapter 2 of this thesis aimed at closing this gap and provide information on possible improved biomass technologies that can be promoted, as well as identify key stakeholders in the sector. It was found that Uganda has a policy to promote sustainable use of biomass technologies. There were a number of organizations promoting use of modern biomass energy including the government, non-governmental organizations and the private sector. However, levels of adoption remain low, and majority of the households still rely on traditional biomass technologies for cooking. The technologies are known to be very inefficient and would result in high rates of biomass resource use. Indoor air emission from traditional biomass use is one of the main health challenges in Uganda. More than 85% of the population live in rural areas, which are sparsely populated. This suggests that small scale standalone energy systems would probably be more viable, since the cost of installation of national grid would be prohibitive. Detailed results of the state of the art review is provided in Chapter 2 of this thesis and in Okello at al., (2013b).

9.1.2 Energy potential residue biomass

An evaluation of the bioenergy potential of agricultural and forest residues established that Uganda had gross potential of about 260 PJ in year 2008, which is equivalent to about 70% of the country's biomass energy requirements. Methods and findings of this analysis is given in Chapter 3 of this thesis and in Okello et al., (2013a) However, utilisation of these residues poses serious organisational challenges, especially the logistical requirements for the supply chains. This is because the resources are scattered over large geographical areas. Cattle manure for example could be used for biogas production, but a large proportion of cattle farmers practice pastoralism or open grazing. Collection of the manure for biogas production would be a challenge. Also it was observed that there were variations in the composition of residues in different parts of the country, suggesting need for customising supply chains for the different agro-ecological regions. Considerations social, economic, environmental and technological aspects were discussed and found to be critical for successful utilisation of biomass residues. For example, residues play important ecological roles; therefore only fraction of it should be recovered for energy use. These issues were discussed in detail in Chapter 3.

9.1.3 Overview of pre-screening results

Often times, efforts to introduced modern energy services in developing countries have not resulted in desired levels of adoption. In some cases, new technologies are faced with rejection by the target population. It is known that increasing participation of stakeholders in decision making increases the chance of public acceptance of technologies. A novel method for participatory appraisal of bioenergy technologies was developed and used in a multi-stakeholder setting to rank four bioenergy technologies in Uganda. Detailed description of the method based on SWOT, AHP and desirability functions is given in

Chapter 5 of this thesis and in Okello et al., (2014). The supplication example in Uganda shows that Jatropha oil system, biogas and briquette energy systems ranked better than charcoal, the reference system. This suggests that stakeholders were willing to accept the relatively new technologies in place of the traditional charcoal technologies.

The proposed participatory appraisal method showed potential of being used as a screening tool in the early phases of planning when there are a large number of alternatives. Those alternatives that perform very poorly based on stakeholder opinion can be identified and removed from further consideration. This would increase the time and resource efficiency during planning. Critical concerns of stakeholders about the energy supply chains can also be identified and possible remedies developed right from the beginning of the planning process. For example, stakeholders identified lack of skilled personnel as a threat to most bioenergy systems. This suggests the need to increase the number of bioenergy technicians. This is seems to be in agreement with findings in Chapter 2, since only one institution was found to be training bioenergy technicians in the country.

9.1.4 Identification and weighting of criteria

Criteria provide the basis on which to benchmark and communicate progress towards sustainability as well as being important inputs to decision making. A set of 21 sustainability criteria for bioenergy systems in Uganda were developed. The criteria were selected on principles of relevance, practicality, independence and simplicity. Weights were assigned to each criterion by a multi-stakeholder panel with the aid of the AHP methodology. Economic and social dimensions of sustainability were ranked highest in importance, followed by environmental and technical dimensions, respectively. Investment and operating costs were the ranked as the most important criteria. This could perhaps be explained by the low level of per capita income of Ugandan households. It suggests that efforts to reduce costs of biomass technologies, such as provision of subsidies could enhance sustainability of the systems. Environmental dimension ranked third in importance, unlike in Europe where is ranked most important by other scholars (Buchholz et al., 2009). This is probably due to a lower level of environmental awareness amongst Ugandan stakeholders compared to their European counterparts. Detailed description of the methods used for criteria selection, ranking along with results obtained and discussions are given in Chapter 6 of this thesis.

9.1.5 Environmental impacts of energy systems

Use of biomass for cooking could result in environmental impacts along the supply chains. This study evaluated the environmental performance of domestic biogas, briquette gasification, charcoal and Jatropha cooking energy systems. The aim was to identify hotspots along the supply chains, and to generate environmental criteria for the MCDA phase of this study. A comparative life cycle assessment (LCA) of the four model energy systems was carried out, with results showing that biogas is the most environmentally sustainable alternative, while charcoal had the worst environmental performance. Environmental performance of biogas and Jatropha systems were observed to significantly improve with recycling of by-products as fertilizer. Biogas exhibited the lowest level of reparatory inorganics followed by briquette gasification in TLUD stoves. This suggested that biogas could have the highest potential to reduce human health impacts due to indoor air pollution. Details of the methods used in the study of environmental performance of the four energy systems together with results and discussion are given in Chapter 7 of this thesis.

9.1.6 Multi-criteria sustainability assessment

Sustainability assessment of biomass energy systems requires that social, economic, environmental and technological concerns are integrated into the decision making process. These are conflicting objectives for which multi-criteria analysis is well suited. A multi-criteria methodology based on PROMETHEE and GAIA methods was developed and used under Ugandan conditions for assessing sustainability of biogas, briquette and Jatropha energy systems with charcoal as the reference system. Under the business as usual scenario, charcoal and biogas were found to be incomparable basing on the PROMETHEE I partial ranking but better than Jatropha and briquette gasification systems, which were also found to be incomparable. However, with improved recycling of by-products, biogas ranked first, followed by Jatropha and charcoal, while briquette ranked last. The GAIA analysis was used as a descriptive tool to help understand the relationship between criteria and alternatives. Detailed description of method used, results obtained and detailed discussions are presented in Chapter 8 of this thesis.

9.2 Limitations and proposal for suggestion for future research

The main limitations of this study concerns the quality of data used in the analysing the alternatives and methodological constraints for quantifying social and technological criteria. The LCA phase of the study in particular had a major challenge with availability of both foreground and background data required for the analysis. Basically, primary data from Uganda that could be used for the LCA study were not readily available. Therefore, effort was made to obtain foreground emission data from studies carried out in other developing countries with similar technologies. Nevertheless, some of the emission data such as for the stoves were of similar technologies but obtained under laboratory conditions. In many cases, there can be a difference between laboratory and field performance of a technology.

Also, it was not possible to find background emission data for transport and electricity under developing country conditions. Therefore emission data for transport and electricity under the European conditions were used for modelling the LCA study. This could affect the overall accuracy of the results presented in this study. This suggests the need for future studies aimed at improving data quality for sustainability studies on biomass energy systems in developing countries. Provision of field data would provide better insight to the actual performance of the technologies.

The study also faced methodological challenges for evaluating the technical and social criteria. Currently there are well-developed methods for evaluating economic criteria, for example using LCC. Environmental criteria can also be evaluated using the LCA methodology. However, social criteria such as acceptability were generally evaluated based on subjective judgement. In this study, expert opinion was used to evaluate social criteria. Though it is generally acceptable to use expert judgement in such situations, the results are prone to flaws. Similar difficulties were faced during evaluation of technological criteria. This suggests the relevance of effort aimed at developing quantitative evaluation methods especially for the technological criteria.

Generally, there are several scenarios that could be developed for each of the supply chains evaluated in this study. This provides an opportunity to explore possible improvement to each supply chain using the same methods used in this study. Due to limitations of the scope of this study, only a few scenarios were developed and evaluated.

Exploring different scenarios could provide more insight to the available opportunities to increase the sustainability of each of the supply chains.

9.3 Conclusions

The following are the main conclusions from this study:

1. Bioenergy systems currently used for cooking in Uganda are inefficient and pose high health risks to users. The level of adoption of improved technologies generally remains low. Similar trends are reported in available literature concerning biomass energy use in developing countries, most especially in sub-Saharan Africa.
2. Agricultural and forest residues could significantly contribute to reduction of forest biomass requirement in Uganda. However, social, economic, environmental and technological constraints could hinder their utilisation.
3. Economic and social factors play a predominant role in the decision by Ugandan households to adopt sustainable bioenergy technologies for cooking. This suggests the need for development of low costs technologies and/or provision of incentives to ensure sustainable development of the bioenergy sector.
4. The life cycle environmental performance of biogas and Jatropha energy systems significantly improves with increase in recycling of by-products as fertilizers, and avoidance of open air burning of residues.
5. Recycling by-products as fertilizer significantly improves overall sustainability of biogas and Jatropha bioenergy systems. This observation suggests that integration of energy and food production could significantly increase their sustainability.
6. Results of this study suggest that biogas energy system is more sustainable compared to Jatropha plant oil, briquette gasification and charcoal systems. Biogas showed high potential to reduce indoor air pollution; therefore, suggesting its use could result in positive health benefits.
7. The method developed for participatory appraisal of bioenergy systems, based on strength weaknesses opportunities an threats (SWOT), analytic hierarchy process and desirability functions seem to be a very promising tool for decision making.
8. The proposed multi-criteria sustainability methodology based on PROMETHEE and GAIA methods showed high potential for use as tools for assessing sustainability of bioenergy systems used for cooking in developing countries.

Appendix A – Numerical example for generating Figure 5.5

First, the SWOT group priority values in third column of Table A3 are transformed into a multi-criteria decision matrix, as illustrated in Table A1.

Table A1. Multi-criteria decision matrix of the current study

Criteria	Alternative technologies			
	Biogas	**Charcoal**	**Jatropha**	**Briquettes**
Strengths (S)	0.182	0.156	0.217	0.397
Weaknesses (W)	0.306	0.216	0.132	0.278
Opportunities (O)	0.391	0.145	0.481	0.180
Threats (T)	0.121	0.485	0.172	0.144

Next, the values of SWOT factors given in Table A1 are transformed into desirability values ranging between 0 and 1. Desirable attributes, i.e., strengths and opportunities should be maximised and therefore transformed using Equation 5.6 In Equation 5.6, $w_{\min j}$ is the lowest value of each criterion, given in Table A1, while $w_{\max j}$ is the highest. For the case of strengths, $w_{\min j}$ = 0.156, and according to Equation 5.6, it transforms to a desirability value of 0. Also, $w_{\max j}$ = 0.397, which transforms to a desirability value of 1 according to Equation 5.6.

Intermediate values, w_{ij} are 0.182 and 0.217, can be transformed using Equation 5.6 as [(0.182 – 0.156)/(0.397 – 0.156)], and [(0.182 – 0.156)/(0.397-0.156)], which yield 0.108 and 0.253, respectively. Values of opportunities can be similarly transformed using Equation (6). Following a similar argument, values of weaknesses and threats can be transformed into desirability values using Equation 5.7. The result of this process is given in Table A2.

Table A2. Desirability values of the criteria of each technology

Criteria*	Desirability of alternative technologies			
	Biogas	**Charcoal**	**Jatropha**	**Briquettes**
d_S	0.108	0.000	0.253	1.000
d_W	0.000	0.517	1.000	0.161
d_O	0.172	0.000	1.000	0.104
d_T	1.000	0.000	0.860	0.937

*d_S, d_W, d_O and d_T are desirability values of strengths, weaknesses, opportunities and threats, respectively.

Assuming equal weight of 0.25 for each of the criteria, the overall score of biogas technology can be calculated using Equation 5.8 as (0.108*0.25) + (0.000*0.25) + (0.172*0.25) + (1.000*0.25), which yields 0.320 as the overall score of the technology. The overall scores of charcoal (0.13), jatropha (0.78) and briquettes (0.55) technologies can be calculated in a similar manner and the results used to plot Figure 5.5.

Table A3. SWOT factors and their rankings as identified by stakeholders

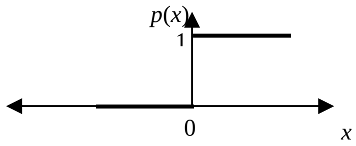
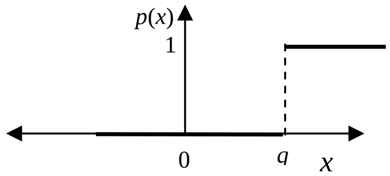
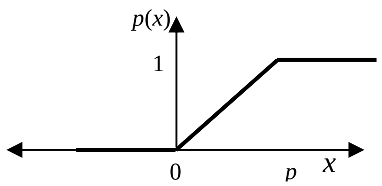
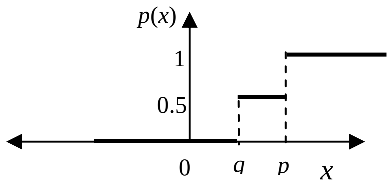
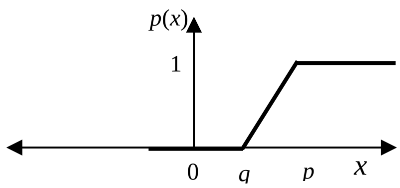
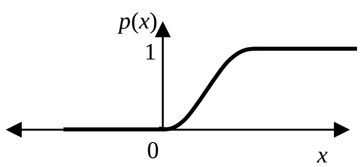
Technology	Energy technology	Group priority	SWOT Factors	Local priority	Global priority	Brief description of SWOT factors
Biogas	Strengths	0.182	Saves time	0.149	0.027	Requires less time to operate compared to fuelwood collection
			Energy security	0.342	0.062	Ensures households are secure of energy supplies
			Health benefits	0.312	0.057	Reduced indoor pollution leads to better health of users
			Hygienic	0.198	0.036	Anaerobic digestion sanitises livestock waste
	Weakness	0.306	High investment cost	0.255	0.078	Capital cost is high for average Ugandan households
			Lack of awareness	0.263	0.081	Potential users do not know about benefits of biogas
			Unskilled labour	0.347	0.106	Limited personnel to construct and maintain the technology
			Labour intensive	0.135	0.041	High labour requirements for day-to-day system management
	Opportunities	0.391	Increasing demand	0.354	0.138	Demand for the technology is known to be rising
			Source of income	0.189	0.074	Possible income from sale of gas and digestate as fertilizer
			Job creation	0.166	0.065	Employment in the value chain, mainly masons
			Decentralised power source	0.291	0.114	The plants are family owned so have better control over their operational performance
	Threats	0.121	Low social acceptance	0.207	0.025	Low acceptance is mainly due to lack of awareness
			Competition from charcoal	0.405	0.049	Charcoal is widely used and accepted therefore limiting adoption of the new technology
			Health risks of manure handling	0.112	0.013	Currently manure handling is done manually (by hand) and could pose risk to transmission of cattle disease to users
			Inadequate raw material	0.277	0.033	Many households do not have cattle to supply manure
Charcoal	Strengths	0.156	Easy to use	0.212	0.033	Simplicity of the technology enables its ease of operation
			Highly reliable	0.394	0.061	Less prone to shutdowns due to system failure
			Widely available	0.394	0.061	Charcoal and stoves are readily available on the local market
	Weakness	0.216	Poor handling properties	0.235	0.051	Easily crumbles into small particles during handling
			High losses to low efficiency	0.241	0.052	Wastage of charcoal occurs during use due to inefficient combustion appliances
			Lead to indoor pollution	0.271	0.058	Due to emissions of poisonous gases and particulate matter
			Non uniform in quality	0.255	0.055	Quality is not consistent due to varying source of wood used
	Opportunities	0.145	Job creation	0.101	0.015	Employment in the production and sale of charcoal and stoves
			Income to rural economy	0.344	0.050	Charcoal is a major source of income to rural households
			Easily adaptable to local conditions	0.392	0.057	Technology is simple and can easily offer opportunity to be easily adopted/improved to local conditions
			Very cheap	0.164	0.024	Potential savings by households due to low capital an operating costs

Table A3 continued …

	Threats	0.485	Deforestation	0.403	0.195	Currently there is rapid loss of vegetation in Uganda
			Climate change	0.132	0.064	Emissions from charcoal could contribute to climate change
Charcoal			Indoor pollution	0.072	0.035	Indoor pollutants have negative health impacts on users
			Land use change	0.394	0.191	Undesirable change in land use due to wood harvesting leading to loss of biodiversity
Jatropha	Strengths	0.217	It is renewable	0.360	0.078	It is a renewable energy source
			Availability of carbon credit	0.171	0.037	This is an incentive for using renewable energy under cleaner development mechanism (CDM)
			Weather resistant	0.218	0.047	Jatropha plant is grows in adverse weather conditions
			Easy propagation	0.251	0.054	Availability and ease of propagation from seeds and cuttings
	Weakness	0.132	New and not widely used	0.329	0.043	Being new technology, it is not known by potential users, thus limiting its adoption
			Limited market	0.177	0.023	Under developed market system for Jatropha technology
			Long gestation period	0.229	0.030	Plant time lag from planting to sustainable yield of 3 to 5 years
			Land competition	0.265	0.035	Competition for land for other productive activities
	Opportunities	0.481	Opportunity for research	0.255	0.123	Opportunity to develop biodiesel, soap and medicines
			Improves soil and climate	0.249	0.119	Jatropha reduces soil erosion and microclimate in areas where it is grown
			Job creation	0.311	0.149	Employment in the value chain of Jatropha energy system
			Has medicinal value	0.186	0.089	Jatropha products could be used for treatment of ailments
	Threats	0.172	Poisonous nature of oil	0.296	0.051	The oil is poisonous and can be health and safety hazard
			Competition with charcoal	0.242	0.041	Charcoal is so far very popular could be a limiting factor to Jatropha use
			Inadequate expertise	0.207	0.036	Inadequate organisational capacity to develop the technology
			Competition with crop production	0.256	0.044	Diversion of resources to Jatropha production could lead to food insecurity
Briquettes	Strength	0.397	Multiple uses	0.166	0.066	Possibility to use in variety of locally available cooking devices
			Waste management	0.184	0.073	It is a suitable method for managing agricultural waste
			Reduces deforestation	0.364	0.144	Due to substitution of charcoal
			Clean and easy to handle	0.287	0.114	Has better handling properties than charcoal and do not crumble easily
	Weakness	0.278	Lack of awareness	0.200	0.055	Potential users do not know about benefits of briquettes
			High investment cost	0.527	0.147	Briquetting machines are expensive for average household
			Inadequate skill	0.274	0.076	Limited skilled personnel to maintain the technology
	Opportunities	0.180	Job creation	0.352	0.063	Employment in the value chain of briquetting
			Increased demand	0.206	0.037	There is growing demand for briquettes
			Improved living standard	0.233	0.042	Use of briquettes lead to better living conditions due to reduced labour requirements for wood fuel collection
			Favourable policies	0.210	0.038	Government policies encourages use of renewable energy
	Threats	0.144	Unskilled labour	0.106	0.015	Lack of skilled artisans required for briquette production
			Lack of support industry	0.263	0.038	Electricity, roads and other infrastructure required from briquetting
			Low social acceptance	0.359	0.052	Low acceptance mainly due to lack of awareness
			Inadequate expertise	0.272	0.039	Inadequate organisational capacity for the development of briquetting industry

Appendix B – Common preference functions used in PROMETHEE method

Table B1. Preference functions, p(x)* and parameters required for preference modelling

Type	Name of function	Mathematical expression	Illustration of preference function	Required parameters
I	Usual criterion	$p(x)=\begin{cases}0, & for\ \forall x \le 0\\ 1, & for\ \forall x > 0\end{cases}$		-
II	U-shape or Quasi criterion	$p(x)=\begin{cases}0, & for\ x \le q\\ 1, & for\ x \ge q\end{cases}$		q[a]
III	V-shape criterion	$p(x)=\begin{cases}\frac{x}{p}, & for\ 0 \le x \le p\\ 1, & for\ x \ge p\end{cases}$		p[b]
IV	Level criterion	$p(x)=\begin{cases}0, & for\ x \le q\\ \frac{1}{2}, & for\ q < x \le p\\ 1, & for\ x > p\end{cases}$		p,q
V	Linear with indifference area criterion	$p(x)=\begin{cases}0, & for\ x \le q\\ \frac{x-q}{p-q}, & for\ q < x \le p\\ 1, & for\ x > p\end{cases}$		p,q
VI	Gaussian criterion	$p(x)=\begin{cases}0, & for\ x \le 0\\ 1-e^{-\frac{x^2}{2\sigma^2}}, & for\ x \ge 0\end{cases}$		s[c]

[*] $x = f_j(a_1) - f_j(a_2)$

[a] q is indifference threshold and represented the largest deviation considered to be negligible by the decision maker,

[b] p is threshold of strict preference that is the smallest deviation considered sufficient to generate full preference

[c] s the inflection of the Gaussian criterion and has a value between p and q

Appendix C – Financial assumptions

Assumptions for calculating unit costs and IRR for the energy systems

It was assumed that the biogas unit is supplied by manure generated by three heads of cattle. Each head of cattle produces 2.67 kg volatile matter (VM) per day, with a biochemical methane potential of 0.2 m^3 kg^{-1} VM (Okello et al., 2013a). The plant is assumed to operate for 365 days a year, leading to production of 11,695 MJ of biogas, with a higher heating value (HHV) of 20 MJ kg^{-1}. Biogas is assumed to be 80% of the unit cost of LPG. A 16 kg bottle of LPG cost Uganda Shillings 130,000. Assuming the HHV of LPG to be 48.9MJ kg^{-1} (Zamfirescu and Dincer, 2009) the unit cost of biogas would be Uganda Shillings 150 MJ^{-1} of biogas. Cattle manure was assumed to be a by-product with an allocation of 10% of total cost of grass production, price of cattle and burn construction. The remaining 90% cost is allocated to production of dairy products.

Briquette system assumed that material collection is done once a week, with each trip ferrying 400 kg of maize stalk. This results in an annual production of 20.8 t of briquettes per year. The total capital costs, which includes procurement, installation and commissioning of the briquetting plant was estimated to be Uganda Shillings 15,840,000. Annual operating costs amounted to Uganda Shillings 21,694,000. The cost of low energy briquette in Uganda for was taken to be USD 0.23 kg^{-1} (EEP, 2013). This results in a gross annual income of Uganda Shillings 24,254,880 and net profit before tax of Uganda Shillings 2,694,880.

Charcoal system required a capital cost of Uganda Shilling 400,000. The annual operating costs, consisting of mainly labour and transport was evaluated to be Uganda Shillings 23,900,000. The unit cost of a kilogramme of charcoal was assessed to be Uganda Shillings 500, basing on 2013 market price. Annual gross profit before tax was therefore calculated to be Uganda Shilling 2,080,000.

Jatropha production assumed a plantation of 2 ha at a yield of 5000 kg ha^{-1} per year. Investment cost was evaluated to be Uganda Shillings 14,300,000, including procurement and installation of oil press. Annual operating cost was evaluated to be Uganda Shillings 2,950,000. Production of oil begins in the fourth year, reaching a steady yield in the fifth year. The cost f Jatropha oil was assumed to be the same as that in Northern Tanzania at USD 0.93 per litre (Wahl et al.). Gross profit in the fourth year was estimated to be

Uganda Shillings 929,701. This increases to a steady level of Uganda Shillings 1,859,402 in the fifth year.

The above information was used to calculate the IRR of each technology and results given in Table A 8.2. The IRR is defined as the discounted rate at which the total net present value after tax is equal to zero (Hu et al., 2014). For calculation, it was assumed that energy from biomass is not taxed.

Table C1. Cash flow for the energy systems and IRR results (Uganda Shillings*)

Cash flow	Biogas	Briquette	Charcoal	Jatropha
Capital investment	-3,240,000	-15,840,000	-400,000	-14,300,000
Net income Year 1	754,000	2,694,880	2,080,000	-1,859,402
Net income Year 2	754,000	2,694,880	2,080,000	-1,859,402
Net income Year 3	754,000	2,694,880	2,080,000	-1,859,402
Net income Year 4	754,000	2,694,880	2,080,000	929,701
Net income Year 5	754,000	2,694,880	2,080,000	1,859,402
Net income Year 6	754,000	2,694,880	2,080,000	1,859,402
Net income Year 7	754,000	2,694,880	2,080,000	1,859,402
Net income Year 8	754,000	2,694,880	2,080,000	1,859,402
Net income Year 9	754,000	2,694,880	2,080,000	1,859,402
Net income Year 10	754,000	2,694,880	2,080,000	1,859,402
Net income Year 11	754,000	2,694,880	2,080,000	1,859,402
Net income Year 12	754,000	2,694,880	2,080,000	1,859,402
Net income Year 13	754,000	2,694,880	2,080,000	1,859,402
Net income Year 14	754,000	2,694,880	2,080,000	1,859,402
Net income Year 15	754,000	2,694,880	2,080,000	1,859,402
IRR	22%	15%	520%	1%

*1 USD is approximately 2530 Uganda Shillings in March 2014

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