# Implications of improved biofuel management for climate change

## An LCA-based evaluation of biochar and charcoal in Kenyan smallholder farming

### Master thesis

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# Abstract

Diminishing fuel sources, polluting cooking techniques and soil degradation compromise the livelihoods of Kenyan smallholder farmers. To address these challenges, the research project “Biochar and smallholder farmers in Kenya” studies the introduction of domestic gasifier stoves that produce char from locally available biomass, besides providing energy for cooking. While cleaner combustion reduces fuel consumption and detrimental emissions, the char can be used as an energy-rich fuel for cooking (i.e., charcoal), or as a soil amendment and means of carbon sequestration (i.e., biochar).

Improved cook stoves, charcoal and biochar have been widely taken up in development research. Yet this thesis identifies three gaps in evaluation which it aims to fill by addressing (1) several goals of sustainable development; (2) alternative ways to source and convert biomass feedstocks; and (3) trade-offs between charcoal and biochar. Based on the Life Cycle Assessment methodology, two strategies of improved biofuel management are compared with the current practices. A dynamic model developed for this purpose calculates each system’s climate impact when delivering the required amount of cooking energy. Furthermore, the model accounts for fuel consumption, soil amendment and detrimental pollutant emissions.

Irrespective of modelling approach and parameter settings, the charcoal and the biochar system show clear advantages over the baseline. Applying char to soil is the best option as it reduces the climate impact by 85-157% depending on pollutant set and time frame; causes the lowest level of indoor air pollution; and allows for the agronomic benefits of 831 kg biochar per hectare and year. However, if organic resources are scarce and unsustainably harvested, it may be better to use char for energy and thus save primary feedstocks. In practice, not only fuel use efficiency and soil amendment, but also stove handling and usability will determine how farmers use available feedstocks.

Keywords: Life Cycle Assessment, Global Warming Potential, improved cook stoves, top-lit updraft gasifier, solid biomass fuels, energy efficiency

## Zusammenfassung

Brennstoffknappheit, ineffiziente Kochtechnologie und degradierte Ackerböden gefährden die Lebensgrundlage kenianischer Kleinbauern. Um diesen Herausforderungen zu begegnen, untersucht das Forschungsprojekt „Biochar and smallholder farmers in Kenya" den Einsatz von Vergaseröfen, die aus lokal verfügbarer Biomasse Pflanzenkohle produzieren und gleichzeitig Energie zum Kochen liefern. Während der Pyrolyseprozess Rohstoffverbrauch und schädliche Emissionen reduziert, kann der kohlenstoffreiche Rückstand entweder als Brennstoff zum Kochen (Holzkohle) oder in der Landwirtschaft zur Bodenverbesserung und Kohlenstoffbindung eingesetzt werden (Biokohle).

Verbesserte Kochöfen, Holz- und Biokohle wurden in der Entwicklungsforschung vielfach aufgegriffen. Die vorliegende Arbeit trägt zu einer ganzheitlichen Evaluierung bei, indem sie (1) mehrere Ziele nachhaltiger Entwicklung; (2) alternative Brennstoffe und Einsatzmöglichkeiten; und (3) den Nutzungskonflikt zwischen Holz- und Biokohle einbezieht. Ausgehend von der Ökobilanz-Methodik vergleicht sie zwei Strategien für verbessertes Brennstoffmanagement mit der derzeitigen Praxis. Zu diesem Zweck wurde ein dynamisches Modell entwickelt, das neben Klimaauswirkungen auch Rohstoffbedarf, Bodenverbesserung und gesundheitsschädliche Emissionen bilanziert.

Sowohl das Holzkole- als auch das Biokohle-System zeigen klare Vorteile gegenüber der Ausgangslage, unabhängig von Modellierungsansatz und Parameterwahl. Die Ausbringung von Pflanzenkohle auf Ackerböden ist aus agronomischer Sich, aber auch für Raumluftqualität und Klimaschutz die beste Option. Sind Rohstoffe jedoch knapp und nicht nachhaltig geerntet, hat die Nutzung von Holzkohle als Energieträger den Vorteil eines geringeren Rohstoffbedarfs. In der Praxis sind nicht nur Unterschiede in Energieeffizienz und Bodenverbesserung, sondern auch Handhabung und Einsatzmöglichkeiten der Kochöfen entscheidend dafür, ob sich Pflanzenkohle für Kleinbauern als alltagstauglich erweist.

Schlagworte: Life Cycle Assessment, Global Warming Potential, verbesserte Kochöfen, Top-Lit Updraft Vergaserofen, feste Biomassebrennstoffe, Energieeffizienz

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# Abbreviations and acronyms

| | |
|---|---|
| AfDb | African Development Bank Group |
| BC | Black carbon |
| BOKU | University of Natural Resources and Life Sciences Vienna |
| C | Carbon |
| cap | Capita |
| CDIAC | Carbon Dioxide Information Analysis Center |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| d.b. | Dry mass basis |
| EC | Energy consumption |
| EC JRC | European Commission, Joint Research Centre |
| EF | Emission factor |
| EM | Earth mound kiln |
| FAO | Food and Agriculture Organization of the United Nations |
| FC | Fuel consumption |
| F-gases | Fluorinated gases |
| $f_{NRB}$ | Fraction of non-renewable biomass |
| $f_{RC}$ | Fraction of recalcitrant carbon |
| GDP | Gross domestic product |
| GJ | Giga joule |
| GNI | Gross national income |
| GoK | Government of Kenya |
| GWC | Global Warming Commitment |
| GWP | Global Warming Potential |
| ha | Hectare |
| hh | Household |
| HHV | Higher heating value |
| ICRAF | World Agroforestry Centre |
| IEA | International Energy Agency |
| IITA | International Institute of Tropical Agriculture |
| ILCD | International Reference Life Cycle Data System |
| ILO | International Labour Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Organization for Standardization |
| KCJ | Kenya Ceramic Jiko |
| LCA | Life Cycle Assessment |
| LHV | Lower heating value |
| LPG | Liquefied petroleum gas |
| LU | Lund University |
| Md | Moisture on a dry mass basis |
| MJ | Mega joule |
| MoE | Ministry of Energy (and Petroleum) |
| MRT | Mean residence time |
| $N_2O$ | Nitrous oxide |
| NCE | Nominal combustion efficiency |

| | |
|---|---|
| NEMA | National Environment Management Authority |
| NMHCs | Non-methane hydrocarbons |
| NRB | Non-renewable biomass |
| OC | Organic carbon |
| OECD | Organisation for Economic Co-operation and Development |
| PIC | Products of incomplete combustion |
| PM | Particulate matter |
| RB | Renewable biomass |
| SLU | Swedish University of Agricultural Sciences |
| $SO_2$ | Sulphur dioxide |
| SOC | Soil organic carbon |
| SOM | Soil organic matter |
| TC | Total carbon content |
| TLUD | Top-lit updraft (gasifier) |
| TSP | Total suspended particles (in pollutant mass) |
| TSPC | Total suspended particles (in carbon mass) |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| w.b. | Wet mass basis |
| WHO | World Health Organization |
| WRI | World Resources Institute |

# 1 Introduction

## 1.1 Quick guide through the thesis

Access to clean energy is particularly challenging in sub-Saharan Africa. In Kenya, domestic cooking and heating is the single most energy consuming activity (MoE, 2002, pp. 23–31). The majority of households collect solid biomass (mostly wood) that they combust over open fire in poorly ventilated dwellings. This is not only inefficient in terms of fuel use, it also causes high levels of indoor air pollution and related health hazards. Since more than one third of the global population relies on traditional biomass use (IEA, 2012, p. 532), this has become a key area of research for development. At the local level, the focus lies with basic supply and health protection; but energy security also has an important regional and global dimension. If energy demand is to rise in pace with population growth, increasing fuel efficiency becomes imperative to avoid further degradation of natural resources and climate change.

As a locally available and potentially renewable fuel, biomass has an important role to play in Kenya's future energy system. However, the current practices of raw material sourcing, conversion and combustion need to be revised. During the last decades, improving household cooking technology has received considerable attention, and particularly its leverage potential in rural areas. Through efficient and cleaner combustion, better stoves may yield multiple dividends regarding health, economic opportunities, ecosystem protection, resource preservation, and climate change mitigation (Whitman, Nicholson, Torres, & Lehmann, 2011). More recently, the idea to couple domestic cooking with charring organic material to be used as a soil amendment in agriculture has added a whole new dimension to the existing rationale. Besides improving soil properties in terms of nutrient and water holding capacity, biochar application has the potential to stimulate crop yields and carbon sequestration (Lehmann, Gaunt, & Rondon, 2006, pp. 404–410). Alternatively, charred biomass may serve as a storable and energy-rich cooking fuel referred to as charcoal.

Against the background of declining natural wood stocks and degraded agricultural soils, farming has become a twofold connecting point between energy and food systems. It serves as a sustainable biomass source on the one hand, and as a sink for nutrients and organic carbon on the other hand (Torres-Rojas, Lehmann, Hobbs, Joseph, & Neufeldt, 2011). This comprehensive view on biomass systems opens new opportunities to simultaneously enhance energy availability, fuel use efficiency, on-farm nutrient cycling, and agricultural productivity. However, addressing energy and food security at the farm level is not only interesting in terms of local biomass supply, recovering residues and nutrients. It is also a strategy to empower rural smallholders and to reduce their vulnerability towards market-related or environmental hazards (Harvey et al., 2014; Kaygusuz, 2011). Especially at times of rising energy prices and climate change, self-sufficient and resilient households are less prone to resource scarcity and poverty.

In an attempt to meet the challenges of diminishing fuel sources, polluting cooking techniques and degraded soils, the project "Bio-char and smallholder farmers in Kenya" studies potential benefits of small-scale biochar or charcoal production in rural households (see section 1.2 for an introduction to the project). The goal is to improve energy availability, health, life quality, and crop productivity by optimising the use of farm-level organic resources. To this end, the research project encompasses several components. The energy component evaluates gasifier stoves that can be used for charring biomass and cooking food at the same time, with a focus on efficiency and emissions from combustion. The soil component explores how biochar affects crop productivity and soil properties. With a view on rural people's livelihoods and development prospects, the Biochar Project also deals with socio-economic implications.

Building on previous project results, the aim of this thesis is to evaluate scenarios of improved resource use against the traditional practices in rural Kenya. It screens alternative biomass sources and utilisation pathways, with Embu county serving as case study site. By identifying leverage points to mitigate climate change and health effects, the results shall improve the basis for decision-making and future project design. A life cycle approach accounts for greenhouse gases (GHG) emitted from biomass sourcing to final placement and thus prevents biases due to burden shifting within the system. Section 1.3 defines and delimitates the aim and scope of the present thesis in more detail.

The first sections of chapter 2 provide an overview of Kenya's socio-economic structure and link it to aspects of sustainability. This background helps to understand why biomass energy and smallholder farming are key entry points to promote sustainable development in sub-Saharan Africa. Section 2.3 explains current practices and challenges regarding four areas that are essential for rural livelihoods, namely energy, health, agriculture, and environment. Building on this, the next section presents options for improvement and preliminary results of the Biochar Project. Following the methodological framework to quantify climate impacts in Life Cycle Assessment (LCA) in chapter 3, chapter 4 describes the three systems to be compared in this thesis, namely (i) traditional practices as a reference; (ii) charcoal to energy; and (iii) biochar to soil. Based on the results regarding the systems' performance and climate impacts in chapter 5, chapter 6 and 7 discuss benefits and challenges of implementing the alternative systems at rural farms in Kenya. Moreover, they address strengths and limitations of the empirical framework developed in this thesis.

## 1.2 The Biochar Project

The project "Bio-char and smallholder farmers in Kenya" (henceforth referred to as "the Biochar Project") studies potential benefits of small-scale biochar or charcoal production in rural households. In an attempt to meet the challenges of diminishing fuel sources, polluting cooking techniques and degraded soils, it suggests four joint measures:

1. broadening the resource base by using farm-level organic resources
2. combining cooking and heating with the production of charred biomass
3. applying more efficient stove technology for cooking and char production
4. using the charred biomass as a soil amendment in agriculture (i.e., biochar) or as a cooking fuel (i.e., charcoal)

Char is the product of carbonising biomass, a process of thermal decomposition under limited oxygen supply. In principle, carbonisation is the same process as pyrolysis, but it focusses on generating solid char rather than wood-gas or pyrolysis oil (Roth, 2014, pp. 13–14). While char used as a fuel is called charcoal, it is referred to as biochar when applied as a soil amendment. Hence, charcoal and biochar are two terms for the same product that specify the intended way of using it (Lehmann & Joseph, 2009, pp. 1–3).

The research evaluates the introduction of household stoves that produce char through carbonisation of locally available biomass, while at the same time providing thermal energy for cooking and heating. The first hypothesis is that combining these processes in closed stoves reduces fuel consumption and indoor emissions affecting people's health. Secondly, the project aims to demonstrate the benefits from using the char either as a soil amendment allowing for carbon sequestration (i.e., biochar), or as a high quality fuel for cooking (i.e., charcoal). Based on the findings from household surveys, cooking tests and pot trials, the goal is to propose better ways of using farm-level organic resources.

The first phase of the Biochar Project[1] runs from 2013 to 2016 and is funded by the Swedish Research Council. Three coordinated projects follow between 2016 and 2018. Given its interdisciplinary nature, the research builds on a cooperation of the Swedish University of

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[1] Visit the project website at http://www.slu.se/bio-char-kenya for details on project partners, funding and related publications.

Agricultural Sciences (SLU) in Uppsala, Sweden; Lund University (LU) in Lund, Sweden; the International Institute of Tropical Agriculture (IITA) in Nairobi, Kenya; and the World Agroforestry Centre (ICRAF) in Nairobi, Kenya. There are three study sites in the counties of Embu, Kwale and Siaya in order to account for the variety of agro-ecological conditions and farming systems in Kenya (see subsection 2.3.3). As mentioned earlier, biochar and improved cook stoves for rural households have attracted considerable attention in recent research. When it comes to implementation, however, local conditions and socio-economic aspects need to be taken into account (Mahmoud, Röing de Nowina, Sundberg, & Njenga, forthcoming). With this in mind, the research project follows a holistic approach that comprises three main pillars:

1. **Energy:** assess gasifier stoves for charring biomass and cooking regarding energy use efficiency, quantity and quality of biochar output, and indoor air pollution, depending on the input material used;
2. **Soil:** assess how different types of biochar affect soil biological, chemical and physical properties, as well as their impact on crop productivity; and
3. **Socio-economic potential:** evaluate the implementation of char production and use as a smallholder technology and assess its effects on rural livelihoods.

Section 2.4 provides details on how the work packages have been implemented so far and which benefits the project measures may realise in practice.

## 1.3 Objective and definition of the research topic

The thesis builds on the rationale, scope, and preceding results of the Biochar Project. As an overall objective, the improved management of organic resources at farm level shall contribute to energy availability, health, crop productivity and climate change mitigation. To this end, the project proposes four strategies, namely (1) substituting on-farm biomass for primary fuel wood; (b) recovering the waste heat from charring biomass for cooking; (c) introducing improved stove technology; and (d) using charred biomass as a soil amendment (i.e., biochar) or as a cleaner fuel (i.e., charcoal).

### 1.3.1 Aims and structure of the thesis

The present thesis aims to evaluate the four project measures jointly against the traditional practices in Kenyan smallholder farming. For this purpose, it performs an environmental assessment considering all life cycle stages from biomass sourcing to final usage or placement. To meet the needs of Kenyan smallholder farmers, the evaluation accounts for two major services: (1) providing sufficient cooking energy at the household level, which is considered mandatory; and (2) agricultural soil amendment including carbon sequestration, which is treated as a non-mandatory side-effect of biochar application. The LCA methodology provides the framework for a fair comparison of alternatives and avoids burden-shifting within one of the systems. As an internationally standardised procedure (see ISO, 2006a, 2006b) with comprehensive rules for implementation (see European Commission, 2010), it facilitates the exchange with related studies.

Due to practical limitations of this thesis, the scope of the LCA is restricted to climate impacts, whereas other effects are discussed in qualitative terms. The life cycle approach deepens the understanding of sources, sinks and proportions of greenhouse gases and other climate forcing agents. In this regard, renewable biomass supply, stove efficiency and carbon sequestration are the key factors to be considered. Whilst the suggested changes in traditional practices are minor and thus likely to be accepted by local farmers, they have significant potential to improve energy use efficiency and yield co-benefits in other areas of life (e.g., higher soil quality and agricultural productivity; time saved to be dedicated to education or income generating activities).

The research done in order to achieve the aim of the thesis can be divided into three steps:

**As a first step**, the thesis investigates the current practices of household cooking and heating on the one hand, and soil management on the other hand. This background is important for the subsequent LCA because it helps to understand gains and trade-offs resulting from alternative ways to source, convert and use biomass. More specifically, it gives an idea about entry points and potential drawbacks of the project measures, and about the current patterns to be superseded. In order to embed the research into the framework of the United Nations' (UN) Sustainable Development Goals, section 2.3 is divided into

1. energy supply and demand;
2. health, equality and opportunities;
3. soil quality and agricultural productivity; and
4. climate and ecosystems.

**As a second step**, the thesis develops a consistent framework to evaluate the biochar and the charcoal pathway against the traditional practices. Based on local conditions and restrictions in Embu county (e.g., regarding biomass availability, energy needs, stove technology, etc.), it presents three systems that allow for a fair comparison in a case study approach:

1. traditional practices as a reference (baseline);
2. gasifier and charcoal for energy provision; and
3. gasifier and biochar for soil amendment including carbon sequestration.

**As a third step**, it performs a Life Cycle Assessment on the climate impacts of the biochar and the charcoal system, and compares them to the performance of the current practices in Embu. The results from LCA and the subsequent sensitivity analysis shall help to identify leverage points to mitigate climate change, thereby improving the basis for future project implementation.

### 1.3.2 Research gaps and contributions of this thesis

Neither improved cook stoves, nor the use of charcoal or biochar are novel to Kenyan smallholder farming and have been evaluated in previous literature. Yet, several questions are still open. This section explains the remaining research gaps and how this thesis attempts to fill them.

**Research gap 1:** Char-producing cook stoves seem a promising solution to remedy many of the problems faced by rural smallholders in eastern Africa. Yet, it is no one size fits it all approach. The benefits of biochar application are highly sensitive to char and soil properties (Sohi, Krull, Lopez-Capel, & Bol, 2010, pp. 63–67), which can only be determined at a local level. Hence, a first step to optimise the use of farm organic resources will be to tailor any solution to local circumstances. Within the project framework, several field studies have evaluated selected project measures regarding their socio-economic potential, fuel consumption, indoor air quality, cooking time, soil properties, or plant growth (see section 2.4). However, none of the studies covered the full project scope, which would allow to identify synergies with other goals for sustainable development as presented in section 2.2. Moreover, the biochar and the charcoal pathway involve trade-offs with alternative uses of biomass that have to be compensated for. This raises the need for a comprehensive evaluation of different utilisation options, including co-benefits and opportunity costs.

**Contribution (step 1):** The present thesis visualises the links between organic resources management and rural livelihoods over the full project scope regarding energy, health, agricultural productivity, climate and ecosystems.

**Research gap 2:** Previous LCA studies on charred biomass commonly focus either on the production or on the use phase, or they are limited to agricultural or energy application. Frequent research subjects include the assessment of

- different stove types for pyrolysis and combustion;
- different feedstocks and fuels (i.e., primary fuelwood from forests, on-farm woody biomass, agricultural residues from different crops, or charcoal);
- different options for the use of charred biomass (i.e., biochar vs. charcoal);
- different application conditions (i.e., soil type, conditions and management);

or combinations of selected aspects. Since interrelations between distinct life cycle phases or use options have experienced a lack of attention, co-benefits or opportunity costs often lie beyond the research scope. By applying system dynamics modelling to biochar production and use in Kenyan farm households, Whitman et al. (2011) accounted for flows and feedbacks occurring throughout the life cycle, e.g. between biomass sourcing, pyrolysis and agricultural production. However, the Biochar Project requires to integrate (i) the co-production of heat for cooking during carbonisation in the gasifier and (ii) the alternative use of charcoal as a fuel. Scholz et al. (2014, pp. 75–97) included the former aspect in an LCA on biochar in western Kenya, whereas the direct comparison to charcoal use seems to be novel in the context of household cook stoves.

**Contribution (step 2):** The thesis develops systems for a consistent comparison, which cover the full project scope, i.e., both the biochar and the charcoal pathway, and simultaneous cooking and char production in rural households.

**Research gap 3:** Given the locally available feedstocks, stove preferences, char utilisation, and application conditions of biochar, further research is needed regarding climate effects. While improved stove technology delivers benefits in both the charcoal and the biochar system, there is a trade-off between energy provision and soil amendment. Depending on comparative advantages, optimising the use of farm-level organic resources has considerable potential for climate change mitigation. Thereby, all stages throughout the life cycle should be considered in order to avoid biased decisions.

**Contribution (step 3):** The thesis presents a Life Cycle Assessment on climate impacts from biomass sourcing to final use or placement to

- account for opportunity costs of alternative biomass uses;
- deepen the understanding of influencing factors; and
- identify leverage points for climate change mitigation.

### 1.3.3 Delimitation

In contrast to a technology assessment under standardised conditions, this thesis follows the people centred approach of the Biochar Project. Building on small-scale technology, the systems take into consideration

- traditional practices and preferences;
- organic resources available at the farm level;
- household energy needs for cooking;
- stove performance under practical use in the field; and
- local soil conditions and farm management.

Since these factors are highly variable, the assessment is tailored to a model farm in Manyatta Constituency, Embu County, where several field studies have been conducted as part of the

Biochar Project. The choice of parameters and the resulting characteristics of the model farm are explained in section 4.

Ideally, a Life Cycle Assessment integrates all impacts occurring throughout the life span of a product or system (ISO, 2006b). However, in accordance with the study's goal and its intended application, an assessment may be limited to selected impact categories and the corresponding inventory data (European Commission, 2010, pp. 108–111). Although climate LCAs are often restricted to direct radiative forcing due to emissions of GHG, this thesis additionally covers other pollutants and action schemes in a separate scenario. Nevertheless, the Global Warming Potential (GWP) covers only one impact pathway of many (IPCC, 2013, pp. 710–712). Since improving energy systems from a climate perspective usually goes hand in hand with renewable sources and fuel use efficiency, it will simultaneously contribute to other impact categories such as stratospheric ozone depletion or respiratory inorganics (Scholz et al., 2014, pp. 49–87). However, there is also a risk of trade-offs, for instance regarding health if renewable but low quality fuels are used (Roth, 2014, pp. 36–37). This concern is further discussed in chapter 6.

### 1.3.4 Hypothesis

The overall hypothesis is that the four above mentioned project measures improve fuel use efficiency and carbon sequestration to such an extent that both improved systems individually outperform the traditional practices in terms of climate change mitigation. Specifically, it is expected that the joint measures lead to

- higher availability of potential energy feedstocks (i.e., biomass suitable to be used as a cooking fuel);
- higher fuel use efficiency and cleaner combustion;
- lower fuel consumption;
- lower pressure on Kenya's woodlands;
- lower emissions from natural decomposition or burning crop residues openly on fields;
- higher rates of carbon sequestration in agricultural soils;
- lower nutrient losses and nitrous oxide emissions from agricultural soils; and
- improved soil properties.

Considering intermediary processes and linkages, these effects lead to a reduction in net emissions of climate forcing pollutants and levels of indoor air pollution of carbon monoxide and particulate matter. In terms of LCA impact categories, a change in cooking and farming practices will thus contribute to climate change mitigation and health protection. Regarding food security, improved soil properties allow for higher agricultural productivity and crop yields. Moreover, a broader resource base and higher fuel use efficiency contribute to energy security.

# 2 Background

This chapter draws a picture of Kenya's socio-economic characteristics and current challenges regarding energy, health, agriculture and environment. Thereby, it helps to understand why biomass energy and smallholder farming are key entry points to promote sustainable development in Kenya. The relationship between organic resources and rural livelihoods provides the basis for the rationale of the project "Bio-char and smallholder farmers in Kenya", which this thesis is embedded in.

## 2.1 Economy, poverty and rural livelihoods

Alongside other East African countries, Kenya has experienced rapid economic development during the last decades. According to the world development indicators (World Bank, 2015), the recent growth in real GDP (gross domestic product) at a rate of 5-6% will continue in the next years. Yet, observed in time series, the indicators reveal that it remains difficult to efficiently translate this growth into poverty reduction, and especially to target those most affected. In 2005, nearly half of Kenya's population lived below the national poverty line, leaving them unable to meet minimum requirements of food and other basic commodities. In terms of per capita income, Kenya lags behind the average level in Sub-Saharan Africa by 25% (World Bank, 2015). The socio-economic country profile in Appendix A provides an overview of key figures and sources presented throughout this chapter.

Two major factors explain the alleged paradox of economic growth and unrelieved poverty, namely increasing population and inequality. With a constant annual growth rate of around 3%, Kenya's population has doubled to over 45 million people within the last 15 years (World Bank, 2015). Besides pressure on natural resources, providing comprehensive and equal access to public services such as health care or education has become a major challenge (NEMA, 2009, pp. 3–4). In a regional comparison, Kenya performs well on social indicators and has achieved considerable improvement. Yet within the country, the benefits are unequally distributed regarding communities, income groups, and gender (AfDB, 2014, pp. 7–8). This imbalance is reflected in the modest GINI index of 47.7 (World Bank, 2015).

According to the world development indicators (World Bank, 2015), poverty is more pronounced in rural regions, both in terms of people affected (i.e., 49% of the rural population compared to 34% of the urban population) and in terms of severity (i.e., 18% poverty gap compared to 11%). This is particularly striking since roughly three quarters of the Kenyan population live in rural areas. Their livelihood is largely dependent on small-scale, subsistence oriented agriculture characterised by low yields, resource scarcity and vulnerability. Major barriers to spur productivity and rural development include a lack of access to markets, credits and technology, poor infrastructure, and an unfavourable regulatory framework (AfDB, 2014, p. 7; Salami, Kamara, & Brixiova, 2010, pp. 8–14). Since farming forms the basis of both food supply and income generation for most rural families, they are particularly prone to impacts of climate change, environmental and market related stressors (Morton, 2007). Limited resources and capacity to cope with shocks leaves them even more vulnerable (Harvey et al., 2014).

While most African countries are agriculture-based economies, recent figures suggest that Kenya has undergone a transition, owing to its rapidly growing service sector. However, although agriculture contributes with less than one third to GDP, it employs 60% of Kenya's working population (World Bank, 2015). Considering informal employment and family labour, the importance of farming for people's livelihoods rises even further. Yet, farmers derive 25-70% of their income from non-farm sources (WRI, 2007, p. 45). This discrepancy is not only due to low labour productivity in agriculture, but also due to the fact that at least half of the sector's output remains subsistence oriented production (NEMA, 2009, p. 4). At the same time, smallholder farmers are the backbone of the country's food supply. As in most East African countries, they cultivate the major part of arable land and produce most of the crop and livestock products (Morton, 2007; Salami et al., 2010, p. 8).

Energy is another sector that is heavily dependent on natural resources, further aggravating the above mentioned dilemma. According to national data, biomass forms the basis of Kenya's energy supply, with charcoal, firewood, farm residues and wood wastes accounting for over 80% of the country's total energy consumption (MoE, 2002, p. 31). However, growing demand and unsustainable sourcing practices have led to land degradation, local deforestation and air pollution (IEA, 2006, p. 427; MoE, 2002, p. 96). The vast majority of the population use firewood and charcoal for cooking and heating, especially in rural areas (KNBS, 2006, p. 248). Given the poor conversion and combustion technology commonly available in households, wood fuels cause serious health hazards and contribute to global warming (Grieshop, Marshall, & Kandlikar, 2011). Since the current patterns of fuel sourcing and use are time consuming and physically demanding, they indirectly compromise equality, education and development prospects (IEA, 2006, p. 428).

Associated with most of the current global challenges, there are two aspects that need to be addressed regarding energy. First, in developing countries, providing basic access to fuel and electricity is a prerequisite for prosperity (Kaygusuz, 2011; MoE, 2002, pp. 95–96). Food production, water supply, health, education and economic opportunities are shaped by energy availability and infrastructure. Besides limited supply, high energy prices continue to be a bottleneck to economic activity in Kenya (Institute of Economic Affairs, 2015, p. 12). Second, where energy systems are in place, societies aim to progress regarding security of supply, efficiency and reducing emissions. Eventually, providing sustainable energy is an essential factor in strengthening economies, protecting ecosystems, improving life quality, and achieving greater equity (UN General Assembly, 2013).

## 2.2 Sustainable development and Kenyan smallholder farming

Kenya's socio-economic and environmental characteristics leave no doubt that smallholder farming has to play a key role in addressing poverty, food and energy security. Coupled with the trends of population growth, economic development and increasing pressure on limited land, reaching these goals seems to be a growing challenge. As reflected in Kenya's National Environment Action Plan (NEMA, 2009, p. 4), there is a risk of poverty and resource depletion being mutually reinforcing. This means that a lack of resources is both the cause and the consequence of environmental degradation regarding

- natural resource stocks as the basis for energy supply;
- soil quality as the basis for agricultural production; and
- climate conditions shaping ecosystems and productivity.

In a long-term perspective, poverty, food and energy security are inseparably tied to healthy ecosystems. Production and consumption patterns that adversely affect the environment compromise future supply, thereby causing the need to compensate for losses in productivity (MoE, 2002, pp. 50–96). Consequences include over-exploitation and land conversion that further aggravate the situation. In Kenya, this interaction has resulted in severe losses of forest cover as well as soil, water and air quality (NEMA, 2009, pp. 4–16). Ironically, the fact of being dependent on natural resources does not lead to more sustainable use when poverty and scarcity are involved. Besides the typical dilemma associated to public open-access goods (Hardin, 1968; Ostrom, 1999), poverty restricts available alternatives and opportunities for improvement. The absence of an adequate land policy and enforcement regime (e.g., undefined ownership rights, free access to ecosystem goods and services, conflicting legislation and institutional mandates) have fuelled these problems in Kenya (NEMA, 2009, pp. 7–35).

At the recent United Nations (UN) summit in New York, the General Assembly adopted 17 goals to improve life quality for people all over the world (UN General Assembly, 2015). Out of the post-2015 sustainable development agenda, four goals are most relevant for the focus of this thesis, with responsible production and consumption serving as a means to achieve them. Figure 1 illustrates the links between the selected four goals and the livelihoods of Kenyan smallholder farmers. The current practices and challenges related to energy, food, health, and environment are presented in section 2.3.

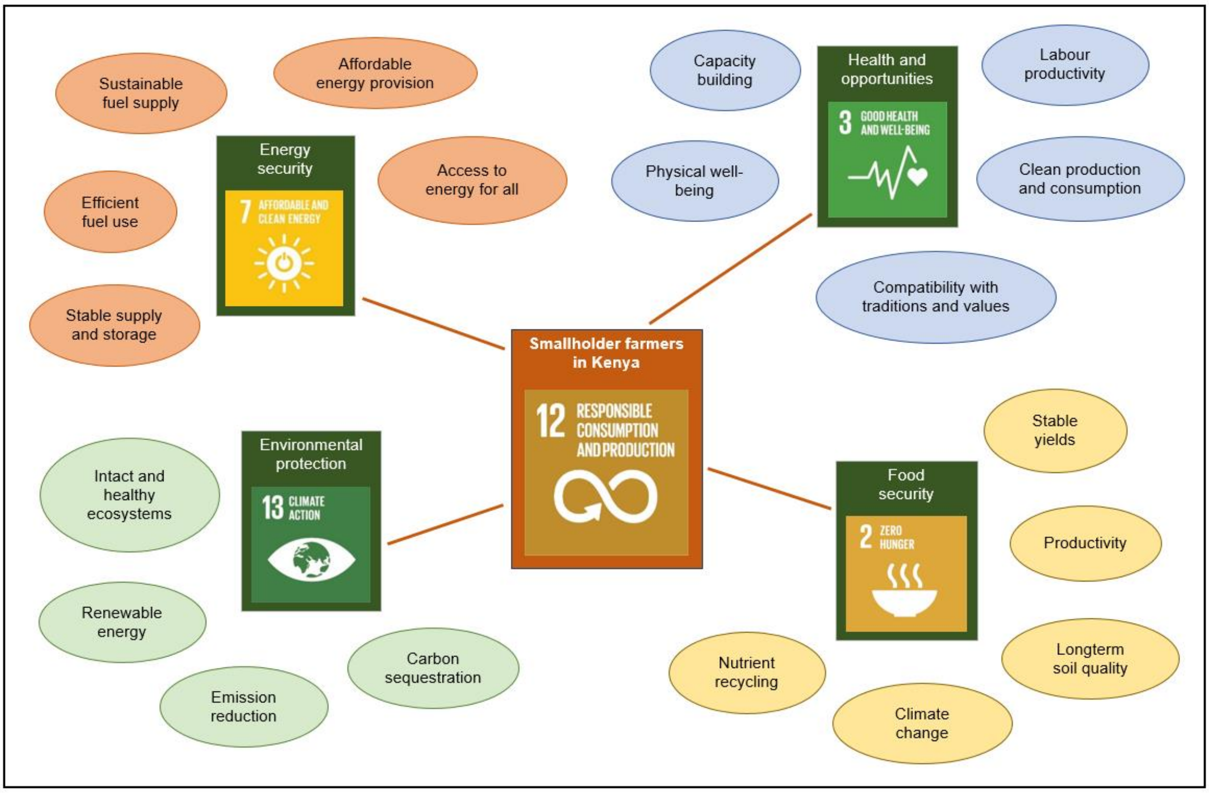


**Figure 1.** Links between Kenyan smallholder farmers and the four post-2015 Sustainable Development Goals selected

According to the African Development Bank (Salami et al., 2010, pp. 8–14), Kenya's agriculture has substantial potential for growth and is four times more effective in reducing poverty that any other sector. Besides providing food and income, farming plays an important role for future energy security. Bearing in mind the lessons learned from the Green Revolution, this development needs to be inclusive and resource efficient in order to allow for long-term and equally distributed benefits (Altieri, Funes-Monzote, & Petersen, 2012; Lehmann & Joseph, 2009, pp. 5–6). For this reason, a bottom-up approach that is sensitive to local needs and conditions, empowers smallholders, and systematically accounts for environmental effects opens great opportunities in handling this challenge.

## 2.3 Current practices and challenges in Kenya

In biomass-based energy and farming systems, the goals of food and energy security, health and environmental protection are closely interlinked. As laid out in the following subsections, the current practices of fuel use and agricultural production are far from being viable in the long run since they compromise their own resource base. Moreover, trade-offs with other Sustainable Development Goals make progress on single aspects questionable.

### 2.3.1 Energy supply and demand

Traditional biomass is the major energy source for poor households in developing countries. The term refers to burning fuelwood, charcoal, animal dung, and crop residues such as maize cobs, stalks or prunings in simple stoves with low efficiencies. The International Energy Agency (IEA, 2012, pp. 529–532) estimated that 2.6 billion people (i.e., 38% of the world population) rely on solid biomass fuels for cooking and heating, whilst 1.3 billion people (i.e., nearly one in five globally) still lack access to electricity. The proportions are significantly higher in developing countries with a high share of rural poor who can hardly afford commercial energy sources such as petroleum, gas, liquefied petroleum gas (LPG) or electricity. In Kenya, traditional biomass supplies 80% of the population as a primary fuel (IEA, 2012, p. 532; KNBS, 2006, p. 248) and covers 97% of household energy consumption (MoE, 2002, p. 31). More than 80% of the population do not have access to electricity, most of them living in rural areas (IEA, 2012, p. 532). Kenyan households usually consume a mix of energy from different sources, whereby the choice of fuels and end-use devices is influenced by accessibility, income, convenience and relative costs (MoE, 2002, p. 90). Poorer families mainly rely on traditional fuels, while the share of modern energy increases with income. Regarding fuel choices and incentives to save energy, it is important to note that relative prices are distorted by the fact that households largely obtain firewood and wood for charcoal for free (MoE, 2002, pp. 74–91; Mutimba & Barasa, 2005, p. 12).

According to national data, wood fuels are the principal source of energy in Kenya (MoE, 2002, p. 31). While petroleum, LPG and electricity do play a role for business and the public sector, household demand (and here especially that of the rural population) dominates the balance with almost three quarters of consumption. Firewood and wood for charcoal deliver equally high shares to the total bioenergy consumption, leaving a small percentage to residues from farming and forestry. For rural households, firewood is the key energy source with a share of almost 60%, since it is easily accessible and compatible with traditional cooking practices. Charcoal is a more expensive and hence less abundant supplement contributing with 30% to rural energy consumption. The remaining 10% are mainly covered by crop residues not used as fodder (MoE, 2002, p. 31). In urban areas, charcoal is the main and cheapest cooking fuel available since it is more suitable for long transport distances, as well as for controlled and more efficient combustion (Institute of Economic Affairs, 2015, p. 26). Figure 2 illustrates the breakdown by sector and fuel type. See Appendix B for the data basis.

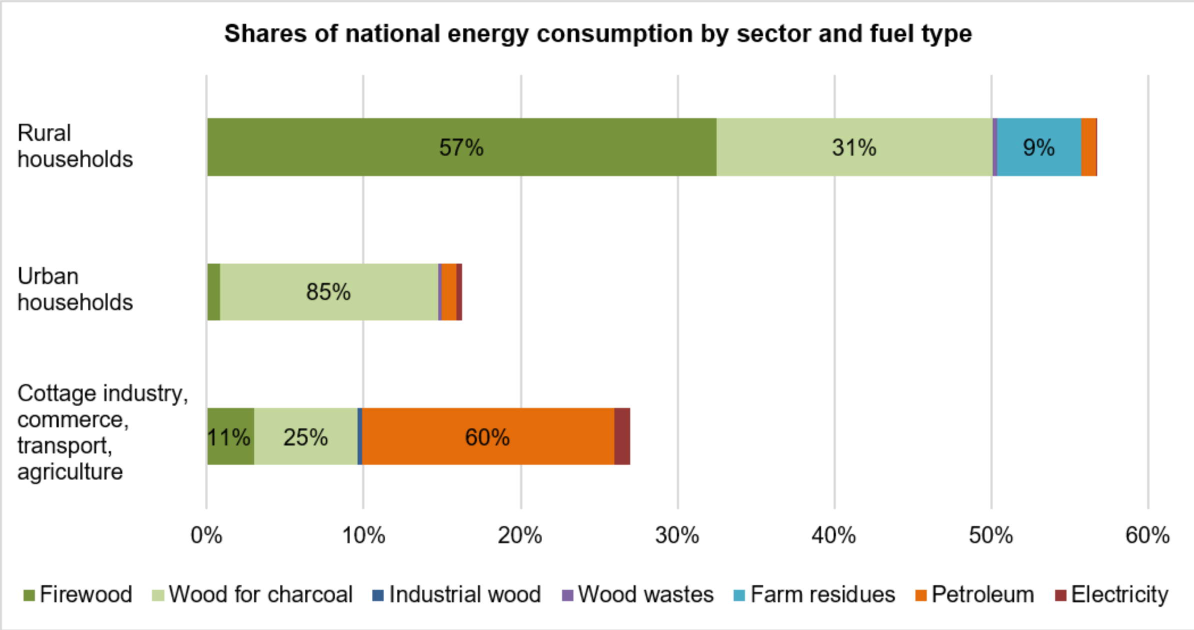


**Figure 2.** Share of Kenya's energy consumption by sector and fuel type: labels in bars indicate the contribution of main fuel types to the consumption of a sector (own compilation based on data from MoE, 2002, p. 31 as presented in Appendix B[2])

As it is locally available and potentially renewable, biomass will and should play an important role in Kenya's future energy system. What needs to be improved, however, are the current practices of raw material sourcing, conversion and combustion in inefficient, polluting kilns and stoves. Since 80-90% of all wood extracted in Kenya is devoted to energy uses (Kenya Forestry Master Plan, 1994, s.p. cited in WRI, 2007, p. 95), fuel sourcing and consumption are key starting points to protect forests and other wooded areas from degradation. For the year 2000, the Kenyan government estimated the gap between demand and sustainable biomass supply at 57%; and the deficit is projected to rise if consumption habits and population growth remain unchanged (MoE, 2002, p. 50). The wider the gap, the higher the amount of wood fuel collected without adequate regrowth or in vulnerable ecosystems. According to the National Environment Management Authority (NEMA, 2009, pp. 4–9), forest loss and degradation have caused a sharp decline in forestry output. Besides the declining resource base for energy and construction purposes, the loss of forests exacerbates erosion, affects water retention and interferes with climate and biodiversity. This has caused siltation of downstream water bodies and land degradation in Kenya's arid and semiarid areas (NEMA, 2009, p. 9).

Over the last three decades, Kenya's wood resources are reported to having been cut by half, leaving the country with less than 2% of closed forest cover (indigenous canopy forests and plantation forests) and 3% of forested area (NEMA, 2009, pp. 3–9). An estimated forest area of 5,000 (NEMA, 2009, p. 9) to 11,000 hectares (World Bank, 2015) is lost each year due to agricultural expansion, settlement and development projects, illegal logging and encroachments, forest fires and over-exploitation. Firewood and charcoal demand have been

[2] The study employed stratified random sampling, with a total of 2,300 households that are representative for rural and urban areas as well as the variety of agro-ecological zones in Kenya (MoE, 2002, pp. 5–7). Considering the publication date, it is likely that the last decade's development has led to changes, especially in the economic sector (e.g., higher share of electricity consumption, increase in total fuel consumption). However, recent research suggests that for rural households, the consumption patterns and associated concerns are still valid (see Njenga et al., 2014; WRI, 2007; Mugo and Gathui, 2010). Nevertheless, other authors point at a lack of up to date consumption statistics (see Drigo, Bailis, Ghilardi, and Masera, 2015).

considered major drivers of deforestation for decades, but this link seems less causal since fuelwood has rather become a by-product of forest clearance for agriculture and settlement (IEA, 2006, p. 427; Karekezi & Turyareeba, 1995; Mutimba & Barasa, 2005, p. 14). Interestingly, the latest assessment of the FAO (2015c, p. 5) reports a forest cover of 7.8%[3]. Moreover, the FAO's time series data show that the trend of forest loss has been reversed since the early 2000s (FAO, 2015c, p. 11). However, these gains might be biased due to changes in measuring and reporting methods on the one hand, and a predominately quantitative assessment on the other hand. Despite being hard to identify and evaluate, characteristics of degradation such as a modified species composition clearly affect forest properties and services (Neufeldt, Langford, Fuller, Iiyama, & Dobie, 2015).

Closed canopy forests can be an important source of wood fuels at a local level, but play a minor role for national energy supply (WRI, 2007, pp. 96–98). This is mainly because the use of natural forests in reserves is strictly regulated by the government[4], whilst plantations mainly deliver timber and poles for construction. A considerable amount of wood for charcoal and firewood comes from natural woodlands, bushlands and wooded grasslands, since their vast expansion of around four times the area of closed forests compensates for the lower tree density (MoE, 2002, pp. 35–37). In response to the low forest cover, Kenya's government has strongly promoted agroforestry to increase the stock of woody biomass (MoE, 2014, p. 50). Indeed, farms deliver a considerable proportion of Kenya's biomass supply, with agroforestry systems being the primary source of fuelwood. The Ministry of Energy reports that the share of fuelwood supplied from farmland grew from around 50% in 1980 to more than 80% in 2000 (MoE, 2002, pp. 11–74). This includes trees and shrubs growing along the boundaries of cropland or roads, vegetation within croplands or woodlots. Moreover, growing resource scarcity incentivises the use of residues from agriculture and wood-based industries such as timber offcuts and rejects, wood shavings and sawdust (IEA, 2006, pp. 427–428; Mugo & Gathui, 2010, pp. 10–11). Appendix B provides background data on Kenya's biomass supply for energy purposes. As Table A4 shows, on-farm sources need to cover 70-80% in a sustainable supply scenario (MoE, 2002, p.41).

As set out in the most recent assessment of wood fuel in Kenya (Drigo et al., 2015, p. 10), a generic interpretation of supply and consumption statistics risks to be misleading, especially in the context of smallholder farming. Forest inventories and supply data cover conventional types and sources of wood fuels such as stems and branches from forestry. In rural areas with low forest cover, however, people cover a high share of their fuel need by using marginal fuelwood such as twigs, small branches and shrubs or other non-conventional resources such as coppice planted on-farm, prunings from farm crops (e.g., coffee trees and tea shrubs) or residues (e.g., maize cobs or coconut husks). The types and availability of biomass depend on region, season and potential alternative uses on-farm such as animal feed. When estimating the self-supply potential, it is important to consider regional farming practices and avoid trade-offs with other systems such as fodder provision and recycling of nutrients. The household consumption level and mix of fuels employed, in turn, also varies by available income and technology (MoE, 2002, p. 90; Mugo & Gathui, 2010, p. 8). To understand the effects of fuel supply and demand in rural areas, it is thus crucial to include data from local or regional surveys, such as those carried out under the Biochar Project (see Gitau & Njenga,

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[3] The figures on forest cover vary greatly depending on the definition of forests, especially concerning minimum canopy cover, height and area. The less strict the definition, the higher the forest cover. According to the UNEP (2001, pp. 8–41), closed forests cover 0.98 million ha (i.e., 1.7% of Kenya's land area), as the UNEP defines closed forests as having min. 40% canopy cover and an interlocking crown. According to the FAO (2015c, p. 5), the forest area is 4.4 million ha (i.e., 7.8% of Kenya's land area), as the FAO defines forests as having min. 10% canopy cover and min. 0.5 ha.

[4] The Kenya Forest Service restricts the use of so called "gazetted forests" regarding daily fuelwood extraction and cutting implements; due to weak enforcement, illegal harvesting may still hamper natural regeneration (Nyambane et al., 2014).

2015; Mahmoud et al., forthcoming). In rural Embu, for instance, the fuelwood available at the local market mainly comes from small scale sourcing that does not differ from collection for subsistence. As soon as larger distances are involved, however, the role and scale of commercial fuelwood rises.

Moreover, the question of how much wood is harvested sustainably cannot be answered based on a national balance of sustainable supply and actual consumption. Applying such a method would require perfect market conditions and zero transportation costs, two assumptions that are far from reality in Kenya. For this reason, Drigo et al. (2015, pp. 7–34) mapped Kenya's sustainable supply-demand balance on a refined spatial scale and came up with scenarios for (a) the use of marginal wood products; (b) the role of commercial supply to account for different transport distances; and (c) different charcoal yield rates. The results show that 35-41% of the annual consumption of wood fuels is harvested unsustainably; by excluding the fraction of marginal woody biomass, this proportion goes down to 31-38% (Drigo et al., 2015, p. 29). The range of values is due to the assumptions mentioned above under (b) and (c). Since the supply figures are not based on current extraction volumes, but on the potential for sustainable harvesting, these results show a clear need for action on the consumption side. In this regard, fuel-efficient stove technology has a key role to play. Given that fuel consumption, wastage and poverty are most pronounced in rural areas, improving cooking and heating for smallholder farmers has a clear leverage potential.

In attempt to avoid the over-exploitation of forests and conversion in inefficient kilns, the Kenyan government regulated the charcoal business by a set of strict rules (Gathui, Mugo, Ngugi, Wanjiru, & Kamau, 2011, pp. 9–19). Consequently, since 2009 the commercial production, transport and marketing of charcoal requires a licence. This applies to every farmer or landowner producing charcoal beyond own household consumption. On the one hand, the fact that the fuel wood sector is becoming increasingly commercialised offers new opportunities to incentivise sustainable supply. On the other hand, though, poor implementation and control mechanisms have opened the gateway for corruption and illegal charcoal to dominate the market (Iiyama et al., 2014). Selling firewood and charcoal produced from wood is an important source of income for rural people, generating up to 20% of household income in well wooded areas (WRI, 2007, pp. 101–107). On this scale, high transaction costs coupled with insufficient awareness and capacity to comply with the rules has pushed many resource-poor farmers into illegal activities. Middlemen have set up a profitable business that, together with transportation costs, keeps the revenue for rural producers low.

According to Iiyama et al. (2014), low economic profits are yet another factor discouraging farmers from improving their production methods. However, the traditional and most common way to produce charcoal in earth mound kilns is highly inefficient. It conserves only 10-20% of the original energy content (MoE, 2002, p. 12; Mutimba & Barasa, 2005, p. 12), whereas improved kilns reach efficiencies of 30% and more (Adam, 2009; Drigo et al., 2015, pp. 7–8; Mugo & Gathui, 2010, p. 24). Examples include retort kilns, brick kilns or improved mound kilns. Nevertheless, over 90% of Kenya's charcoal are produced in earth kilns (MoE, 2002, p. 55). This is first because the kilns are easy to handle, and second because they are constructed at zero monetary cost[5], with natural materials and family labour (Mutimba & Barasa, 2005, p. 12).

[5] The term "monetary costs" is used in distinction to opportunity costs, which do not only account for market prices but for any gains from alternative decisions. Hence, constructing traditional kilns does commonly not involve cash payments, but indeed opportunity costs by detracting time from other activities.

### 2.3.2 Health, equality and opportunities

Lighting an open fire is a prevalent way to provide energy for cooking and domestic heating in developing countries. In rural Kenya, 88% of the households rely on firewood as a main fuel (KNBS, 2006, p. 248). As illustrated in Figure 3, the traditional cook stove consists of three stones supporting a vessel over an open fire place. Hence, it provides little opportunity to control the combustion process or improve the heat transfer (Grieshop et al., 2011). Considering that woody biomass is the main appropriate feedstock for this set-up, the resulting loss in fuel use efficiency is especially problematic in areas where fuel wood is scarce. Not only because it exerts pressure on a declining resource base, but also because it increases the challenge of gathering sufficient wood (Kaygusuz, 2011). Fuel sourcing is a time-consuming and physically demanding task that is mainly carried out by women and children (IEA, 2006, p. 428). In Kenya, rural households spend an average of 14 hours per week on collecting fuelwood, which the majority obtain within a 5-kilometer radius from their home (MoE, 2002, p. 11). Restricting time that may be channelled towards productive or income generating activities, fuel sourcing indirectly compromises equality, education and individual development prospects. Furthermore, average loads of 20 kg of wood or more can lead to long-term physical damages (IEA, 2006, p. 428).

**Figure 3.** Traditional cooking and heating practices: (a) woman carrying 32 kg of fuelwood (Helander & Larsson, 2014, p. 5); (b) three-stone stove in an unventilated dwelling (Njenga et al., 2015); (c) cooking on a three-stone stove (Helander & Larsson, 2014, p. 11)

Cooking over open fire is not only inefficient in terms of fuel use. Incomplete combustion causes emissions of gaseous substances (inter alia, methane ($CH_4$), carbon monoxide (CO) and non-methane hydrocarbons (NMHCs)) and particulate matter (PM) that alter the climate and affect human health (Grieshop et al., 2011). Inside poorly ventilated homes, the smoke from traditional fuel use can bring $PM_{2.5}$ exposure to levels exceeding the WHO Air Quality Guidelines Interim Target for fine particles (WHO, 2014, pp. 41–47) more than 100-fold[6]. Short-term peaks of CO exposure also tend to exceed the guideline values[7]. The World Health Organization (WHO, 2014, p. 1) estimates that every year, over four million people die prematurely from illnesses caused by household air pollution from cooking with biomass and coal. Hence, it is considered to be one of the highest risk factors globally, in terms of deaths and loss of healthy life years (Smith et al., 2014, p. 186). The data suggest that the major non-communicable diseases comprise lower respiratory infections in young children; and stroke, ischemic heart disease, chronic obstructive pulmonary disease, and lung cancer in adults (Grieshop et al., 2011; Smith et al., 2014). Since exposure to household air pollution is driven

[6] WHO Air Quality Guidelines Interim Target for fine particles in settings with high baseline levels: annual mean concentration below 35 µg/m³ to prevent most cases of disease (WHO, 2014, p. 37)
[7] WHO Air Quality Guidelines Target for carbon monoxide: 1-hour average of 35 mg/m³; 15-minute average of 100 mg/m³; 24-hour average of 7 mg/m³ (WHO, 2014, p. 47)

by concentrations and time spent near the source, women and children are disproportionally affected.

Better cook stoves have the potential to improve rural livelihoods via various pathways, with benefits for health and energy availability representing only the immediately visible effects (Kaygusuz, 2011). Secondary gains are related to time savings from higher labour productivity, potential new sources of income, and not least awareness raising and capacity building for future innovations (Karekezi & Turyareeba, 1995). When it comes to implementation, any solution needs to be compatible with local traditions and values in order to allow for practical benefits (Kaygusuz, 2011). In rural Kenya, a cook stove has to be suitable for preparing a traditional meal such as Ugali (cornmeal porridge), Sukuma Wiki (kale fried with onions and tomatoes) or Githeri (maize and bean stew). The latter, for instance, requires low heat supply over a long period, which inevitably hampers the thermal efficiency of a fast combustion process. Since traditional dishes often require long simmering on low heat, cooking methods that allow for regulating fuel input can substantially improve energy efficiency (Sparrevik, Lindhjem, Andria, Fet, & Cornelissen, 2014).

Another factor that needs to be considered is that substituting domestic energy sources and technology is not a purely rational manoeuvre. In a process described as "fuel stacking" by the International Energy Agency (2006, p. 422), households tend to add modern fuels and stoves to supplement traditional practices rather than substituting them. This is partly because of reluctance to modify patterns that work adequately, meaning that new forms of energy are used for selected purposes whereas the supply for basic needs remains largely unchanged. The benefits need to be clearly visible in order to overcome familiarity and individual food taste preferences. Furthermore, households prefer to use multiple fuels to diversify their supply and be less dependent on a single source (Kaygusuz, 2011). These patterns are supported by the results of a household survey conducted under the Biochar Project (see Gitau & Njenga, 2015).

### 2.3.3 Soil quality and agricultural productivity

Agriculture is the principal source of food and livelihoods in Kenya, comprising crop production, livestock rearing, fishing, and hunting-gathering (see section 2.1 and Appendix A). More than any other sector, it is shaped by natural resources and climate conditions. Throughout Kenya, the spatial distribution of livelihood strategies overlaps with the expansion of different ecosystem types; this is especially due to soil properties, temperature and rainfall patterns, considering that most Kenyan farming has to do without irrigation (FAO, 2015a; Kabubo-Mariara & Karanja, 2007; NEMA, 2009, p. 3; WRI, 2007, pp. 43–44). As Figure 4 shows, the medium to high potential agricultural lands in central and western Kenya are dominated by a mix of food and cash crops, as well as dairy cattle. Whilst the fertile land suitable for cropping covers less than 20% of Kenya's land area, it supports 80% of the population (Kabubo-Mariara & Karanja, 2007; Survey of Kenya, 2003 cited in WRI, 2007, p. 43). The remaining share is classified as arid and semi-arid lands that receive low and unreliable rainfall. Since exclusively rain-fed crop production delivers low yields and risks failure in dry areas, pastoral and agro-pastoral livestock rearing is the main livelihood strategy in the eastern and northern parts of the country (WRI, 2007, p. 53). Figure 4 highlights the counties Embu, Kwale and Siaya serving as study sites in the Biochar Project in order to account for the variety of agro-ecological conditions and farming systems in Kenya.

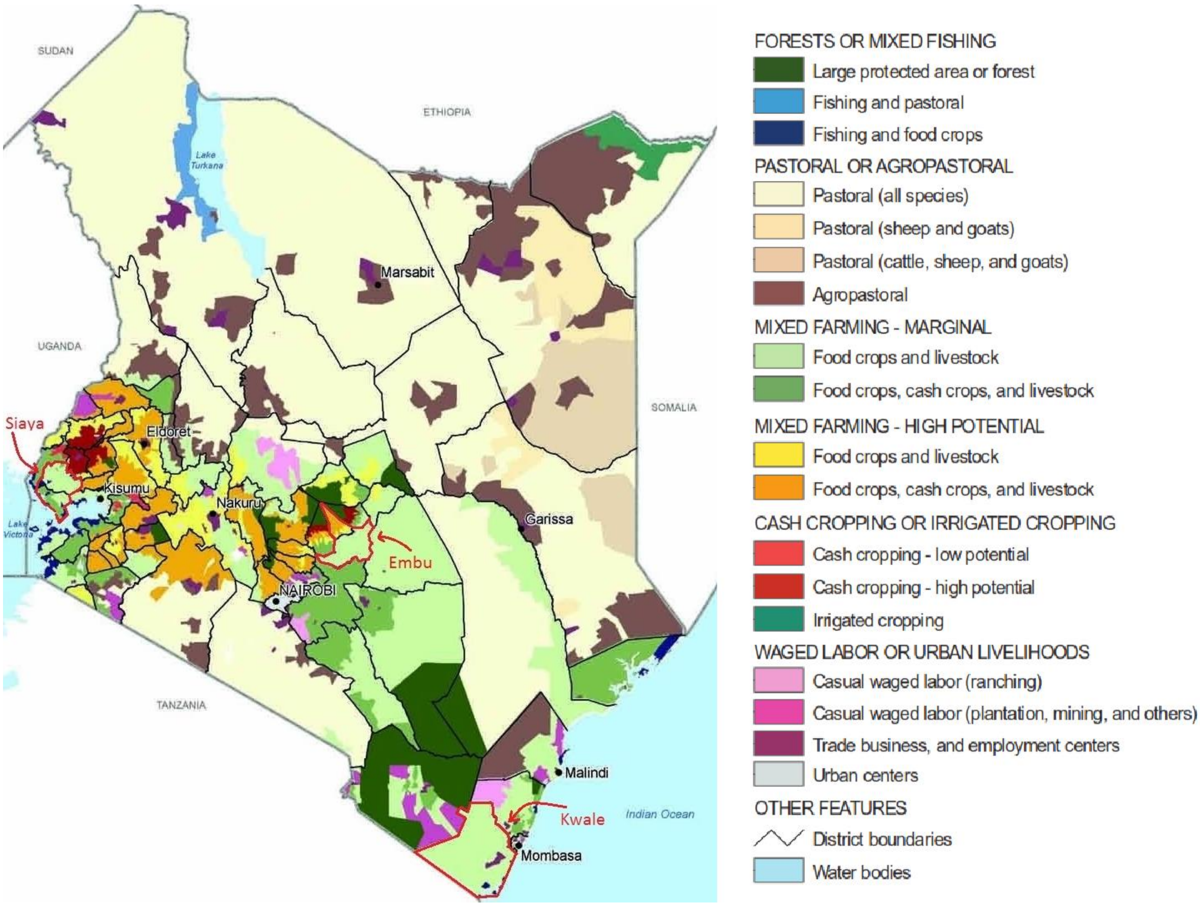


**Figure 4.** Map of Kenya by administrative boundaries: predominant livelihood strategies pursued by households in different regions (2003-2005) and case study sites of the Biochar Project (adapted from WRI, 2007, p. 44)

Cropping and intensive management are concentrated in zones favoured by rainfall and fertile soils. Yet especially for subsistence production, marginal lands in drier areas with shallow soils are also taken under cultivation at a growing proportion (WRI, 2007, pp. 45–46). FAO data on land use show that at national level, the cultivated area has continuously expanded (World Bank, 2015), which exerts pressure on forests, rangelands and dry ecosystems vulnerable to desertification (WRI, 2007, p. 46).

The prevalent food crop in Kenya is maize, both in terms of cultivated area and calories consumed; more than 90% of all households engaged in farming report to grow maize (KNBS, 2006, pp. 189–190; WRI, 2007, p. 48). However, areas with an annual rainfall of more than 800 millimetres, which is considered a minimum benchmark for growing maize and other crops not resistant to drought, account for less than 15% of Kenya's land (WRI, 2007, pp. 26–27). Due to dietary preferences, maize is also planted in regions where neither soil fertility, nor rainfall are adequate. Since the opportunities to compensate by means of chemical fertiliser or irrigation are low, this leads to a high variety in yields, ranging from below 0.5 tons per hectare in semi-arid to over 2.5 tons per hectare in fertile zones (De Groote et al., 2005). Even in high-potential areas, a lack of nutrients limits the output and causes a significant yield gap (WRI, 2007, p. 48). Whilst the cropping area of maize in Kenya continuously expanded between 1985 and 2005, absolute maize output stagnated, corresponding to a 15% loss in productivity (WRI, 2007, pp. 48–50). In light of the growing demand, Kenya has become a net importer of its staple crop by the turn of the century (WRI, 2007, p. 50). Average yields of other food crops such as wheat and rice have remained stable on a growing area, but have not been able to fill the supply-demand gap (WRI, 2007, p. 50). In order to raise returns on land and labour, most Kenyan farmers combine maize production for subsistence with cash crops such as tea, coffee and sugarcane, or food crops such as fruits and vegetables (WRI, 2007, p. 60). Throughout the last 20 years, these high value crops have experienced the greatest expansion rate in terms of cultivated area (WRI, 2007, p. 46).

The soil and climate conditions in Kenya require well adapted farming practices including fallow periods, crop rotation and nutrient replacement in order to deliver sufficient yields (Ståhl, 1993 cited in Söderberg, 2013, p. 11). However, population growth and increasing demand for food have driven continuous cultivation and tillage, agricultural expansion into unsuitable areas and land conversion (Kimetu et al., 2008). Depending on the resilience of an ecosystem, i.e., the degree to which it can be disturbed or burdened until it reaches a tipping point for change, unsustainable land use sooner or later affects productive capacity. Hence, fragile ecosystems such as drylands are more prone to degradation (NEMA, 2009, pp. 2–27). Mismatching natural conditions and farming practices may lead to erosion, acidification, nutrient deficiency, poor soil structure and organic matter content, salinisation, and desertification (Bai & Dent, 2006, p. 1; Kimetu et al., 2008). These signs of degradation pose an increasing risk to food security, ecosystem quality and rural livelihoods. In an attempt to map land improvement and hot spots of degradation in Kenya, Bai and Dent (2006, p. 29) analysed changes in biomass between 1981 and 2003. Accordingly, net primary productivity and green biomass increased overall in woodlands and grasslands, but hardly in croplands. The authors observed a loss in both net primary productivity and rain-use efficiency in 30% of Kenya's croplands, which jointly serves as an indicator for degradation.

Soil properties vary greatly within Kenya, whilst a lack of major nutrients such as nitrogen, phosphorous and potassium can be observed throughout the country (Kabubo-Mariara & Karanja, 2007). Hence, the reasons for limited fertility differ. Arid and semi-arid areas are characterised by shallow, poorly developed soils with low content of organic matter (Kabubo-Mariara & Karanja, 2007). These properties explain a natural nutrient deficiency, which is further aggravated by low water and nutrient retention capacity (Kimetu et al., 2008). In the case of previously fertile soils, the correlation between farm age after conversion and soil degradation reflects the extractive practices widely used by resource-poor farmers in the developing world (Lal, 2006). Rather than improving yields on existing farmland, production grows by expansion, followed by continuous cultivation, tillage, and removal of crop residues for fodder and energy supply (Kimetu et al., 2008). The resulting loss of soil organic carbon (SOC), combined with a shortage of agricultural inputs, degrades soil quality and affects agronomic productivity (Lal, 2006). Kimetu et al. (2008) report losses in maize grain and total biomass yield of 66% during the first 35 years of cropping after forest clearance, even with full inorganic fertilization. These results clearly indicate the importance of long-term preservation of a good soil structure on the one hand, and nutrient replacement on the other hand.

As supported by various field studies, returning organic carbon to soils is a crucial step to reverse degradation, as it improves soil quality in two major aspects: as a short-term effect, organic matter adds nutrients when it is decomposed; in the long run, stable organic carbon enhances soil structure and physical properties, especially regarding nutrient and water holding capacity (Lal, 2006; Sohi et al., 2010, pp. 65–70). While labile materials such as green and animal manure rather supply nutrients, more stable soil amendments such as sawdust or biochar (which has a large fraction of black carbon recalcitrant against biotic and abiotic oxidation) mainly contribute to structural improvement (Kimetu et al., 2008). The latter effect also explains why restoring soil organic carbon may be a precondition for fertilizer to be effective, and less prone to leaching and erosion (Lal, 2006).

The current management of on-farm organic resources leads to considerable losses of carbon, and eventually mineral macronutrients. If biomass does not serve as fodder or fuel, crop residues are openly burned on the field, or left for natural decomposition. If it serves as a feedstock for traditional household stoves, ash might be recycled to soil after combustion. As Figure 5 illustrates, fresh biomass is mineralised within months to a few years, thereby releasing 80-90% of the stored carbon as $CO_2$ to the atmosphere (Lehmann et al., 2006), without providing any energy service or generating a stable fraction. However, if biomass is charred, around 50% of the initial feedstock carbon contribute to energy supply and are released, whereas the remainder is stored in char (Lehmann et al., 2006). Biochar is composed of roughly 80% recalcitrant fraction with a mean residence time (MRT)[8] of 500-1,000 years; this means that the carbon is sequestered long-term before being mineralised and emitted to the atmosphere as $CO_2$ (Roberts, Gloy, Joseph, Scott, & Lehmann, 2010; Whitman et al., 2010). The remaining 20% are labile with a MRT of 15 years (Whitman et al., 2010). Burning biomass openly immediately releases up to 90% of the carbon into the atmosphere (Heard, Cavers, & Adrian, 2006), whereas only 3% are converted into a material equivalent to biochar (Lehmann et al., 2006). This is the case both for open field burning and ash application from a three-stone stove. Figure 6 juxtaposes the three options to recycle biomass in agriculture and their potential to restore soil organic carbon.

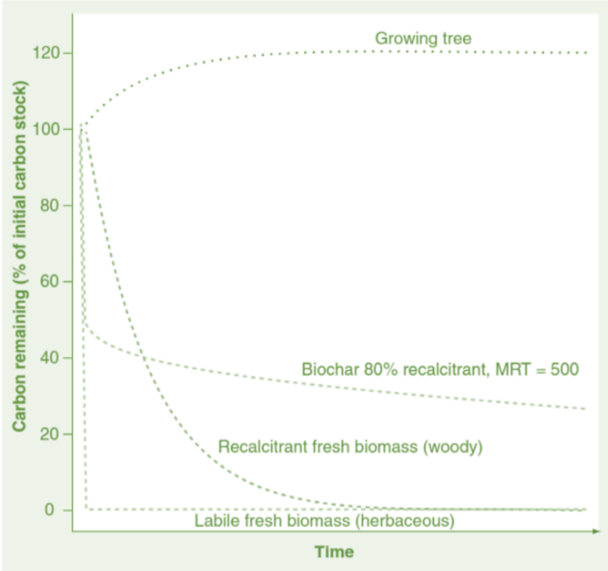


**Figure 5.** Schematic of biomass carbon dynamics: each curve represents the fate of carbon from an equivalent mass of organic matter; in the case of renewable biomass, regrowth compensates for carbon emissions, yet with a time lag (Whitman, Scholz, & Lehmann, 2010)

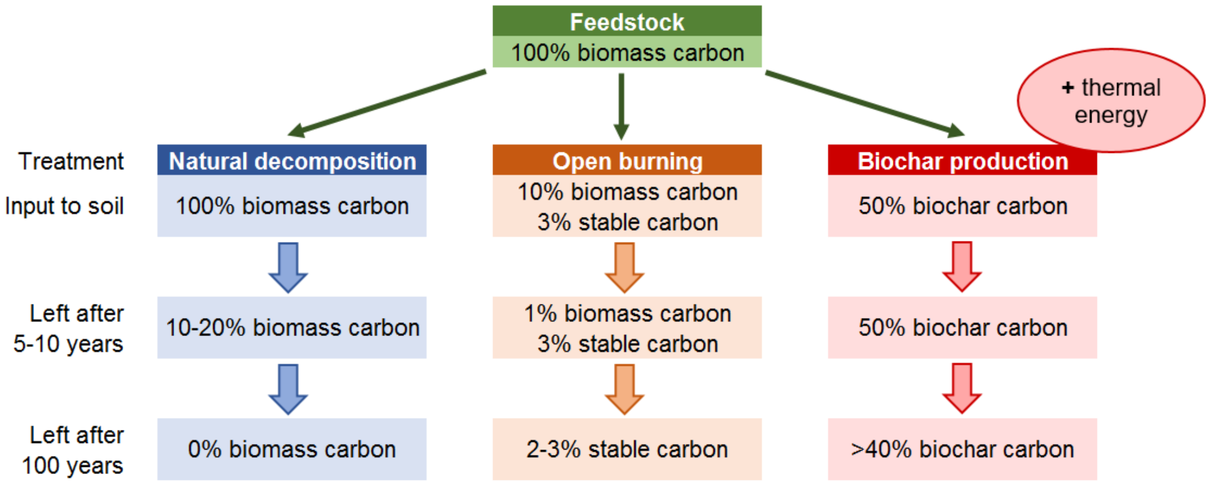


**Figure 6.** Options to treat and recycle biomass in agriculture, and their potential to restore labile and stable soil organic carbon over a short and a long time horizon (adapted from Lehmann et al., 2006)

Left on the field or applied after harvesting, crop residues have important functions to protect the soil against erosion, recycle nutrients and return organic matter; these positive effects should not be overlooked if plant material is devoted to energy supply (Scholz et al., 2014, pp. 56–57; Torres-Rojas et al., 2011). As laid out above, returning biochar to soil performs better than fresh biomass to restore soil organic carbon. Regarding most major nutrients, the

[8] MRT is the time period until the carbon stored in biochar is fully mineralised; when the mineralisation of SOC is modelled in an exponential function, MRT is the inverse of the decay rate (Lehmann, Czimczik, Laird, and Sohi, 2009, p. 185)

properties of charred biomass are as good as those of the original feedstock. Nutrient cycles can almost be closed in a biochar system, as long as equivalent types and amounts of biochar are applied to the site from where biomass has previously been withdrawn. However, the carbonisation process causes losses in nutrients that volatilise, which is the case for nitrogen and sulphur with losses of 50% and more (Scholz et al., 2014, p. 30). The higher the degree of thermal degradation (i.e., on a scale from carbonisation to full combustion), the poorer the solid residue becomes in nutrients. This is reflected in a comparison of fresh biomass, biochar and ashes as soil conditioners by Torres (2011, pp. 40–42), showing that charring oxidises roughly 50% of carbon, nitrogen and sulfur, while other nutrients including phosphorus and potassium are hardly affected[9]; ashes generally contain less than 3% of the original carbon and nitrogen, while around 30% of sulfur and at least 70% of other major nutrients are recovered. A study in Manitoba revealed that open field burning of spring wheat, oat, and flax straw resulted in 98-100% loss of nitrogen, 70-90% loss of sulphur, and 20-40% loss of phosphorus and potassium[10] (Heard et al., 2006). Regarding nutrient uptake and plant productivity, Torres (2011, p. 32) showed that nutrient-rich amendments such as collard green stalks are best applied fresh, whereas nutrient-poor feedstocks such as maize cobs and stovers are most effective when pyrolysed.

### 2.3.4 Climate and ecosystems

In the latest national climate change action plan, the Kenyan Government designates action on climate change a national priority, even though the country has little historical or current responsibility for global perturbations (GoK, 2013, p. 10). Kenya's contribution to worldwide GHG emissions is around 0.15%, with per capita emissions reaching only a quarter of the global average (WRI, 2015; see Appendix C for precise data). Yet, there are several reasons why Kenya's mitigation potential should not remain unused. First, production and consumption patterns that cause global warming are expanding with economic growth and an increasing population. This trend will continuously raise the relative climate impact of rapidly developing countries such as Kenya (GoK, 2013, p. 10). Second, Kenya is highly vulnerable to climate change, as climate-sensitive natural resources form the backbone of the major livelihood and economic strategies in the country. The most susceptible sectors include agriculture, forestry, tourism and hydro-energy (GoK, 2013, p. 12). At the same time, the means to cope with risks and adapt to climate impacts are limited, thereby infringing development options (GoK, 2013, pp. 10–13). Third, from a global perspective, avoiding climate forcing pollutants and fostering carbon sequestration in the developing world is a strategy of picking the low hanging fruits, since the potential has been largely unexploited. However, this argumentation implies that developing countries offer great opportunities for climate action, whereas they should not be responsible for carrying the costs alone.

Already today, over 70% of natural disasters occurring in Kenya are considered weather-related (GoK, 2013, p. 12). Drought is currently the major recurrent natural disaster in Kenya, causing crop losses, famine and population displacement every three to four years (GoK, 2012, p. 42). Furthermore, climate change is expected to drive temperatures and the frequency of hot days and nights, flooding and sea-level rise, as well as drought and water scarcity; precipitation is likely to increase in the highlands and coastal regions, whereas the arid and semi-arid regions will probably become even drier (GoK, 2012, pp. 30–36; GoK, 2013, p. 12). While in the highlands and other fertile zones, agriculture is likely to benefit from increased temperatures and rainfall, vast parts of the country will suffer from declining productivity,

[9] However, the proportion of nutrient mass recovered from the primary material largely varies by feedstock (i.e., collard stalks, maize cobs and stover in Torres (2011)).
[10] While nitrogen and sulphur are lost in form of volatile oxides, the non-combustible phosphorus and potassium are assumed to partly drift away with smoke or particulate matter (Heard et al., 2006).

thereby exacerbating existing regional disparities (GoK, 2012, p. 41; Kabubo-Mariara & Karanja, 2007).

As Figure 7 illustrates, agriculture is the largest source of GHGs in Kenya, causing more than 50% of total national emissions (WRI, 2015). This is mainly due to enteric fermentation and manure management from livestock (i.e., more than 95% of agricultural emissions), whereas the remainder comes from synthetic fertilizers and other agricultural management (FAO, 2015b; WRI, 2015). These proportions are reflected in the relatively high per capita emissions of nitrous oxide ($N_2O$) and methane (see Appendix C). Land-use change and forestry contribute another 14% to Kenya's GHG emissions; this indicator accounts for alterations in terrestrial carbon stocks due to anthropogenic activities such as land conversion and management (including field burning, natural biomass decay and emissions from organic soils) that lead to either net emissions or removals of GHG from the atmosphere (FAO, 2015b). Switching land from natural vegetation to agricultural crops may release high amounts of carbon, not only from above- and below-ground biomass, but also from organic carbon pools in the soil (Sohi et al., 2010, p. 53; Stiebert, 2012, pp. 11–13). Moreover, land conversion entails the expansion of agricultural management, which is associated with diffuse pollution from agrichemicals and organic wastes potentially affecting climate, soil and water resources (Sohi et al., 2010, pp. 54–68). With these factors in mind, it becomes clear that agriculture drives a higher share of GHG emissions than reflected in the single category. As reported in national climate change action plan, the main conversion path between 1990 and 2010 was from unmanaged or extensively managed land use categories (e.g., indigenous forests, bushlands, grasslands) to farms with and without trees, and to a smaller extent to private plantation forests (Stiebert, 2012, pp. 12–13; see also Appendix C).

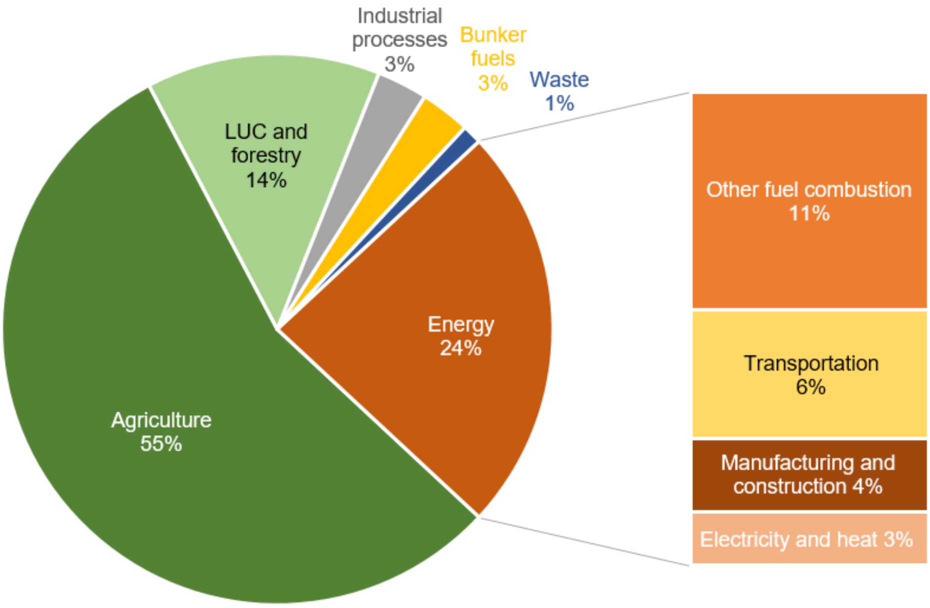


**Figure 7.** Kenya's GHG emissions by sector (left) and energy sub-sector (right): all proportions are relative to Kenya's total GHG emissions in $CO_2$ equivalents (own compilation based on data from FAO, 2015b; IEA, 2013; WRI, 2015 as presented in Appendix C)

With 24%, energy is the second largest contributor to climate forcing emissions. Traditional biomass use in households is part of the aggregated category "other fuel combustion", which accounts for $CO_2$ emissions from fossil fuels, and $CH_4$ and $N_2O$ emissions from biomass combustion as well as stationary and mobile sources (WRI, 2015). This means, that biomass energy is either assumed to draw on sustainable harvesting, or declining carbon stocks have to be covered by the LUC and forestry category. Hence again, the energy sector causes a higher share of GHG emissions than reflected in the single category.

Domestic stoves for cooking and heating are a relevant source of climate forcing pollutants. Yet their potential for climate change mitigation and carbon offsets tends to be underestimated for a couple of reasons. First, the high number of small, scattered sources with varying technology (i.e., different stove-fuel combinations) and fuel consumption is difficult to take into account; second, the prevalent methodology of GHG reporting according to the Kyoto Protocol[11] cannot depict the full climate impact of traditional cooking; third, the proportion of biomass energy that is renewable is uncertain but greatly influences the result; and fourth, sustainably harvested biomass fuels become climate relevant due to incomplete combustion (Grieshop et al., 2011; IPCC, 2013; Johnson et al., 2009; Smith et al., 2000a, pp. 1–4).

Even based on Kyoto emissions alone, traditional cooking merits attention for climate change mitigation. Bailis, Ezzati, and Kammen (2003) suggest that in Kenya, the GHG emissions from production and use of firewood and charcoal exceed those from fossil fuels. Additionally, biomass combustion causes emissions of potent climate forcing agents with a short atmospheric lifetime including black carbon (BC) particulate matter, CO and NMHCs that have a net warming effect, whereas sulphur dioxide ($SO_2$) and organic carbon (OC) particles lead to net cooling (Grieshop et al., 2011). Due to their complex behaviour in the atmosphere, these pollutants were excluded from the Kyoto Protocol (Grieshop et al., 2011). Whilst the relevance of soot for climate change is still contested, Ramanathan and Carmichael (2008) ranked black carbon particles the second largest contributor to global warming, after $CO_2$. The main cause of BC emissions is biomass combustion, with biofuels accounting for 20% (including firewood, charcoal, agricultural residues, and animal dung) and open burning of natural vegetation and crop residues accounting for 42% (Bond et al., 2004). Against this background, Grieshop et al. (2011) argue that the acute and localised climate impacts of black carbon are yet another argument to promote improved stoves. However, it is important to consider that a large fraction of BC from indoor combustion never reaches ambient air; particulate matter is deposited on the roof and walls of dwellings, which rather justifies concern about health than climate (Bailis et al., 2003).

For the sake of simplicity, it is tempting not to account for carbon dioxide emissions from biomass fuels. This is based on the notion that biogenic carbon is entirely oxidised to $CO_2$ and subsequently taken up by photosynthesis in the course of plant regrowth; however, such carbon neutrality would require ideal circumstances regarding sourcing and combustion of biomass (Bailis et al., 2003; Hayes & Smith, 1993, p. 1). As laid out in subsection 2.3.1, less than half of Kenya's biomass supply is based on sustainable extraction (MoE, 2002, p. 50). A rising degree of unsustainable harvesting, henceforth referred to as the fraction of non-renewable biomass (NRB), gives leverage to the climate relevance of biogenic fuels (Whitman et al., 2011). Even under a scenario of 100% renewable biomass (e.g., agricultural residues or sustainably harvested wood), inefficient stoves release products of incomplete combustion (PIC)[12] that cause net warming because PIC have a higher GWP than $CO_2$ (Hayes & Smith, 1993, p. 89).

As a result of poor total energy efficiency (i.e., combustion and heat transfer efficiency), traditional stoves emit high amounts of $CO_2$ and PIC per unit of energy delivered to the vessel (Smith et al., 2000a, p. 3). Since both fuel and stove influence the results, Smith et al. (2000a) assessed 28 fuel-stove combinations that are commonly used in India. On average, the measurements revealed the following ranking of fuel quality with increasing efficiency and decreasing GHG emissions: (a) considering Kyoto gases plus CO and NMHCs: animal dung, non-renewable wood, crop residues, renewable wood, kerosene, LPG, biogas; and (b) considering only Kyoto gases: non-renewable wood, animal dung, crop residues, kerosene,

[11] GWP of $CO_2$, $CH_4$, $N_2O$, sulphur hexafluoride ($SF_6$), hydrofluorocarbons and perfluorocarbons expressed in $CO_2$ equivalents ($CO_2e$) over a time horizon of 100 years (IPCC, 2013, pp. 674–711)

[12] Besides emissions of $CO_2$ and water vapour, incomplete combustion may release CO, $CH_4$, NMHCs and particulate matter (i.e., black or organic carbon particles).

LPG, renewable wood, biogas (Smith et al., 2000a, pp. 3–6). It is important to note that the definition of useful energy in that study exclusively accounts for the purpose of cooking, thereby omitting that diffuse heat emissions contribute to space heating. Nevertheless, the conclusion that solid biomass fuels combusted in inefficient stoves perform worse than fossil alternatives remains valid.

## 2.4 Organic resources at the nexus of energy, health and food security

Interlinked with the major challenges discussed in section 2.3, optimising the use of biomass may yield benefits in multiple areas of life (i.e., domestic cooking and heating, health, education, household budget and income, food production) and aspects of sustainability (i.e., ecosystem and climate protection, resource preservation). This section explains why stove technology and design play a central role in this context. Main factors include compatibility with varying feedstocks, fuel use efficiency, emissions, suitability for people's preferences and the option to produce and conserve char for later uses.

### 2.4.1 Improved stove technology

Various research and extension programs have identified household cooking and heating technology in developing countries as the entry point to mitigate energy related risks. Early efforts in the 1970ies were mainly concerned about deforestation, environmental degradation and human labour for fuel collection (Bailis, Cowan, Berrueta, & Masera, 2009; Grieshop et al., 2011; Karekezi & Turyareeba, 1995; Roth, 2014, p. 5). During the last decades, the focus has shifted towards impacts on human health, particularly from indoor air pollution as strongly emphasised by the WHO (Grieshop et al., 2011; Karekezi & Turyareeba, 1995; Roth, 2014; WHO, 2014). More recently, programmes to promote improved cook stoves for climate change mitigation have gained momentum. In this regard, the financial incentives of the Clean Development Mechanism under the Kyoto Protocol add to the motivation to implement joint projects between western and developing countries (Grieshop et al., 2011; Whitman et al., 2011).

Traditional cook stoves such as the three-stone fire in rural Kenya are characterised by low efficiencies, which is due to heat losses from conduction, convection and radiation, as well as incomplete combustion (MoE, 2002, p. 56). However, it is important to consider that the waste heat from cooking significantly contributes to space heating, which has to be supplied from additional fuel if the heat transfer from stove to pot becomes "too efficient". Although off-heat is mostly produced in excess, it is a relevant factor during cooler seasons, especially in high altitude regions around Mount Kenya (Kituyi et al., 2001a). This aspect has often been ignored in rural development programmes, thus hampering the dissemination of improved cook stoves (Karekezi & Turyareeba, 1995).

According to Grieshop et al. (2011), cooking and heating may be improved in three aspects:

1. ventilation, which is related to dwelling construction;
2. specific emissions, which are determined by the choice of feedstock; and
3. thermal efficiency of the stove, which depends on combustion efficiency (i.e., conversion of the fuel to thermal energy) and heat transfer efficiency (i.e., energy transfer to the intended point).

Despite the importance of modern energy for sustainable development, traditional biomass will continue to supply the basic and most energy consuming services in Kenya, namely cooking and heating (Kees & Feldmann, 2011). As indicated in the context of social factors, the phenomenon of fuel stacking (i.e., adding cleaner fuels to traditional ones rather than replacing them) limits the potential of cleaner fuels to solve the problems related to the use of biomass for energy provision (Kaygusuz, 2011; Roth, 2014, p. 5). Moreover, there is no economic incentive to substitute for wood if it is locally available at zero monetary cost, relying on family labour (MoE, 2002, pp. 74–91). Consequently, improved stoves have mainly been developed and spread for firewood or charcoal combustion; devices that simultaneously optimise combustion efficiency and heat transfer to the pot are most successful in reducing fuel requirements and harmful emissions (Kees & Feldmann, 2011). Improved woodstoves have been developed in different designs, ranging from mud or clay stoves to brick and metal stoves. They usually have an enclosed combustion chamber and may be equipped with an insulated vessel or a chimney (Grieshop et al., 2011). Some stove types are compatible with a wider range of fuels than others. See Table 1 for average efficiencies of different stove-fuel combinations.

**Table 1.** Efficiency of stove-fuel combinations regarding feedstock energy delivered to the vessel; single values from the range are recommended by the author

| Fuel type | Stove type | Efficiency [%] | Source |
|---|---|---|---|
| Firewood | Mud or clay stove | 10 (8-14) | Kaygusuz, 2011 |
| | Three-stone stove | 10-15 | UN, 1987, p. 50 |
| | | 15 (13-15) | Kaygusuz, 2011 |
| | | 16 | MoE, 2002, p. 91 |
| | | 17-19 | Smith et al., 2000, p. 23 |
| | Brick stove | 15 (13-16) | Kaygusuz, 2011 |
| | Metal stove | 25 (20-30) | Kaygusuz, 2011 |
| Charcoal | Mud or clay stove | 15 (15-25) | Kaygusuz, 2011 |
| | Metal stove | 18 | MoE, 2002, p. 91 |
| | Metal stove (ceramic liner) | 25 (20-35) | Kaygusuz, 2011 |
| | Kenya Ceramic Jiko | 30 | MoE, 2002, p. 56 |
| Crop residues | Three-stone stove | 10 | MoE, 2002, p. 91 |

Bailis et al. (2009) report that there have been dozens of improved stove programmes in Africa since the 1980ies, of which only a few turned into success stories regarding adoption and sustained use. Challenges and pitfalls discussed by various authors include commercialisation and marketing, funding and affordability, product quality, adequate design and compatibility with local practices, consumer preferences, additional benefits (e.g., space heating, food taste), engagement of local consumers and manufacturers, awareness, and capacity building (Bailis et al., 2009; Karekezi & Turyareeba, 1995; Kees & Feldmann, 2011). In rural regions, the fact that most households neither pay for their fuel nor for their self-built traditional stoves hampers the dissemination, whereas the adoption in urban areas is easier to achieve (Karekezi & Turyareeba, 1995).

A successful example is the initiative promoting the Kenya Ceramic Jiko (KCJ), a charcoal-burning metal stove with ceramic lining that is fabricated and marketed by artisans (Bailis et al., 2009). By 2001, over two million Kenyan households used a KCJ, which equals around 40% of all charcoal users who mainly reside in urban areas (MoE, 2002, p. 13). Figure 8 shows the typical design of the stove. Compared to the traditional metal stove, the basic appliance for charcoal combustion used in urban households, the KCJ is insulated to increase the heat transfer from the fire to the vessel (MoE, 2002, p. 56).

The market penetration of improved charcoal stoves had reached 47% in 2001, whereas the adoption rate of improved firewood stoves, such as the Kuni Mbili and the Maendeleo Jiko, was only at 4% (MoE, 2002, p. 56). In rural areas, 92% of the households still use the traditional three-stone fire (MoE, 2002, p. 110).

**Figure 8.** Kenya Ceramic Jiko for charcoal use (www.bioenergylists.org)

In biomass-based energy systems, it is worthwhile to broaden the angle for agriculture as a fuel source on the one hand, and as a sink for nutrients and organic carbon on the other hand. In this context, charring biomass at the farm level and using it either as a cleaner cooking fuel (i.e., charcoal) or as a soil amendment (i.e., biochar) has gained attention. Among several initiatives, the Biochar Project combines efficient stoves with the use of farm-level organic resources and the application of biochar and charcoal, respectively.

The central element of the Biochar Project is a gasifier stove for households which combines char production with providing thermal energy for cooking. Thereby, it may substitute the inefficient and polluting practices for both charcoal production (i.e., earth mound kilns) and cooking (i.e., three-stone stoves). In contrast to an open fire, a gasifier separates the two main stages of combustion[13], i.e., gas generation and gas oxidation, both in time and space (Roth, 2014, pp. 13–19). Since each step can be optimised in terms of heat and air supply, this principle allows for a cleaner and more efficient combustion process. Besides vapours, the second product of biomass decomposition (i.e., pyrolysis or carbonisation) is solid carbon-rich char. If primary air is kept from entering the hot char-bed at the end of the conversion phase, char gasification is suppressed and the char can be conserved for later uses as biochar or charcoal (Roth, 2014, pp. 18–24). The option to recover the waste heat from char production for cooking raises the overall fuel use efficiency.

Regarding household application, Roth (2014, pp. 21–23) reports that the main challenge has been to develop a gasifier that is small enough to fit under a cooking pot. This has been achieved in form of the top-lit updraft (TLUD) gasifier, which Roth (2014, pp. 21–26) describes and evaluates in detail (see Figure 9). After pre-tests at the University of Nairobi, a galvanised TLUD gasifier was chosen for the implementation of the Biochar Project. As illustrated in Figure 9 and Figure 10, the three parts of the natural-draft stove comprise (1) an inlet for primary air at the bottom; (2) a fuel container in the middle where carbonisation takes place; and (3) a gas combustion chamber at the top where secondary air enters (Njenga et al., 2015). The cooking vessel is placed on top of the three parts.

Chopped into pieces, the solid fuel is batch fed into the combustion chamber. The portable stove can be lit outside and carried in the kitchen after the fuel has caught fire and stopped smoking (Njenga et al., 2015). As the name indicates, the TLUD gasifier is lit at the top and primary air moves upwards through the fuel container, transporting gases from partial oxidation towards the combustion zone; at the same time, the pyrolytic front migrates downwards, leaving char behind (Roth, 2014, pp. 22–23). In the combustion chamber, the hot wood gases mix with secondary air and are fully oxidised to $CO_2$ and water vapour. When the pyrolytic front reaches the bottom and there is no fuel left to generate combustible gases, the flame naturally dies (Roth, 2014, p. 26). The char is then ready to be taken out of the fuel container and should be covered for 30 minutes to avoid oxidation (Njenga et al., 2015).

[13] The combustion process comprises (1) fuel drying with heat (release of water vapour); (2) pyrolysis or carbonisation with heat (conversion into volatile vapours and solid char); (3) combustion of vapours with oxygen; and eventually (4) char gasification with oxygen (Roth, 2014, pp. 13–16).

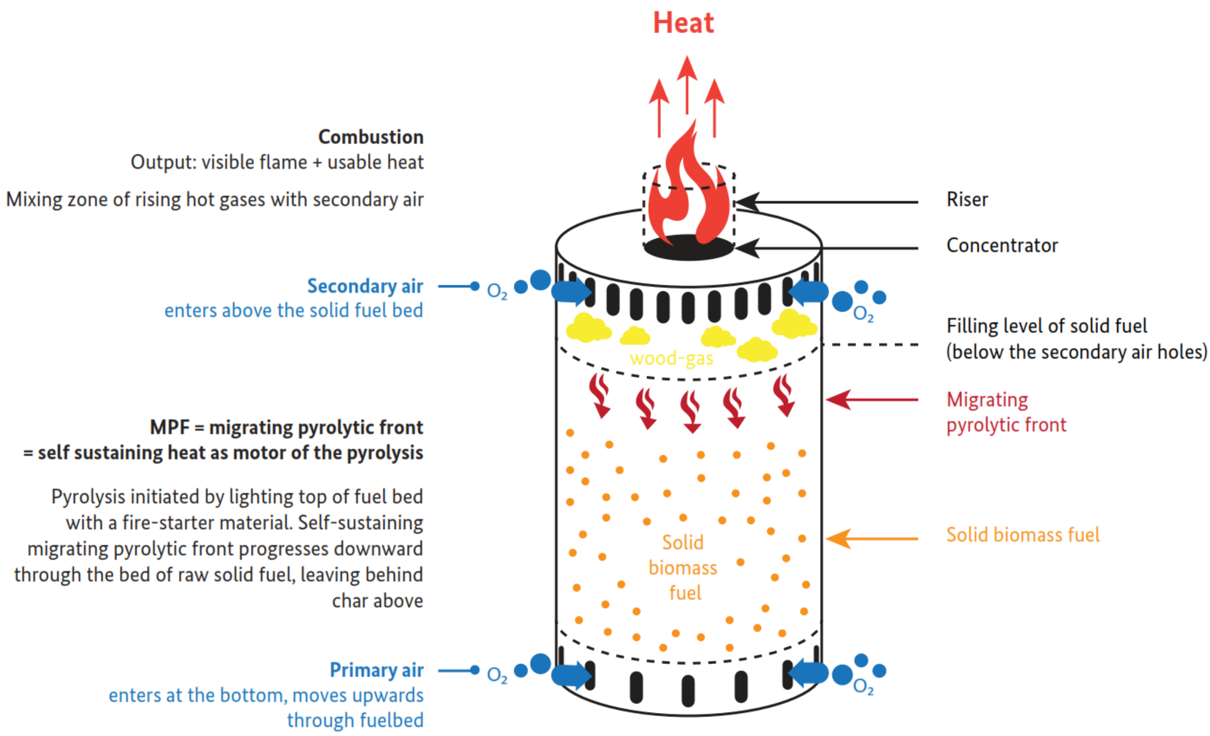


**Figure 9.** Design and basic operation of a char-making TLUD micro-gasifier (Roth, 2014, p. 23)

**Figure 10.** TLUD gasifier: (a) three parts of the gasifier built together (Helander & Larsson, 2014, p. 12); (b) loading the fuel container with crop residues (Helander & Larsson, 2014, p. 12); (c) farmers lighting the gasifier during a workshop in Embu county (Magnusson, 2015, p. 33)

Cooking with a gasifier instead of traditional Kenyan stoves increases the variety of input materials since it uses small pieces of biomass (below a length of 22 cm and a diameter of 3 cm) or even animal dung. Hence, farm-level organic resources such as maize stovers and cobs, coconut shells, coffee husks, and tree prunings can substitute for fuel wood. Besides recovering energy and eventually biochar from low-value crop residues, this measure reduces the pressure on Kenya's woodlands. Mahmoud et al. (forthcoming) studied the availability and current uses of potential feedstocks for charring biomass. The survey among 152 households in Embu, Kwale and Siaya also sheds light on current energy consumption, fuel-stove combinations, fertilizer application and crops grown.

### 2.4.2 Socio-economic potential

Magnusson (2015, pp. 38–39) examined socio-economic factors regarding the use of char-producing stoves and biochar as a soil amendment at the farm level in Embu county. The participating farmers showed a strong interest in experimenting with alternatives regarding domestic energy supply and soil improvement, and expressed their awareness of the impacts that the current practices had on natural resources and ecosystems. The thesis concludes that there is a large potential for the introduction and diffusion of these innovations if they are well aligned with local pre-conditions and preferences.

After training and a test period with the gasifier stove, Gitau and Njenga (2015, pp. 4–6) evaluated its adoption and benefits realized by the farmers. Based on 41 interviews, the authors report on household characteristics, fuel and stove use in practice as well as perceived benefits or drawbacks.

### 2.4.3 Energy efficiency and emissions

Figure 11 gives an overview of the direct and indirect effects of producing charcoal with a TLUD gasifier and saving it as a fuel for later uses, to be burnt in a Kenya Ceramic Jiko. The benefits are related to primary material input, combustion efficiency, emissions, waste heat recycling and charcoal use. Helander and Larsson (2014, p. 34) conducted cooking tests and compared the galvanised gasifier to the KCJ and the tree-stone stove regarding efficiency and emissions. Accordingly, the gasifier saves an average of 41% of fuel input compared to the three-stone fire if the char is used as a fuel. Assuming the purpose of soil amendment where energy is partly withdrawn to store carbon in biochar, it still reduces the fuel consumption by 24%. Improved efficiency saves fuel, the time to obtain it, as well as cooking time, thereby opening new opportunities – especially for women and children. Moreover, the cleaner and more effective combustion in the gasifier reduces pollution, which is known to be detrimental to health and climate. Using the galvanised gasifier, Helander and Larsson (2014, p. 32) report significantly lower indoor emissions of carbon monoxide and particulate matter.

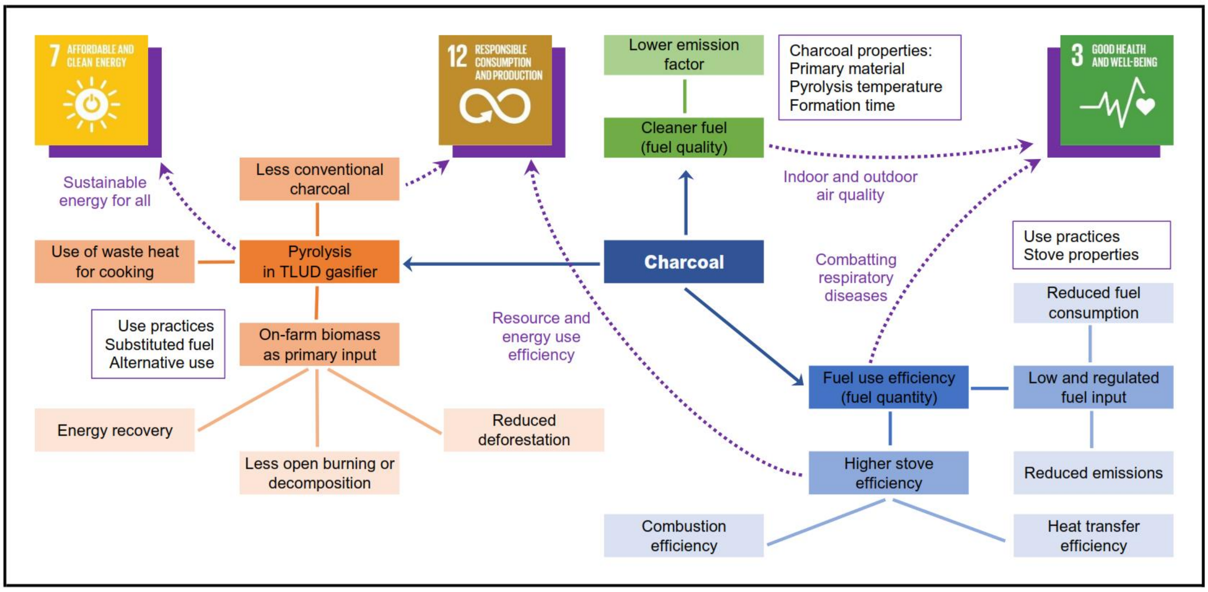


**Figure 11.** Effects of charcoal use as a fuel

A field study in Embu (Achour, 2015, p. 55) did not find a significant difference between the CO and PM emissions caused by charred crop residues and conventional charcoal when used as a cooking fuel in a Kenya Ceramic Jiko. Maize cobs, coconut husks and tree prunings from *Grevillea robusta* were considered as alternative feedstocks. Only in some of the tested households, charred maize cobs showed higher levels of carbon monoxide emissions. Furthermore, the study suggests that using char from crop residues does not lead to a significantly higher mean gross fuel or mean gross energy consumption (Achour, 2015, pp. 22–25). Since the more energy dense charcoal offers a higher fuel quality than the cooking process can exploit, the resulting loss in efficiency levels the playing field for other types of charred biomass (Achour, 2015, p. 55).

### 2.4.4 Soil amendment and carbon sequestration

When applied as a soil amendment in agriculture, biochar raises the content of stable soil organic carbon. Figure 12 gives an overview of direct and indirect effects regarding agricultural productivity, carbon sequestration, fertilizer input and emissions. As reviewed by Sohi et al. (2010, pp. 65–70), the macro-porous structure and cation exchange capacity of biochar improve water and nutrient holding capacity. The physio-chemical properties of biochar and its application rate are the determining factors to this effect. The physical and chemical characteristics of charred organic matter largely depend on the selection of feedstock and the production method, most notably charring temperature and duration. According to Sohi et al. (2010, pp. 63–64), these choices in turn impact on the quality of biochar: pH, content of volatile compounds, content of ash, water holding capacity, bulk density, pore volume, and specific surface area. Until a certain threshold, the carbon content of biochar grows with rising temperature, while biochar yield declines. The outlaid relationship illustrates the leeway for optimising the charring process for specific biochar properties or charcoal use.

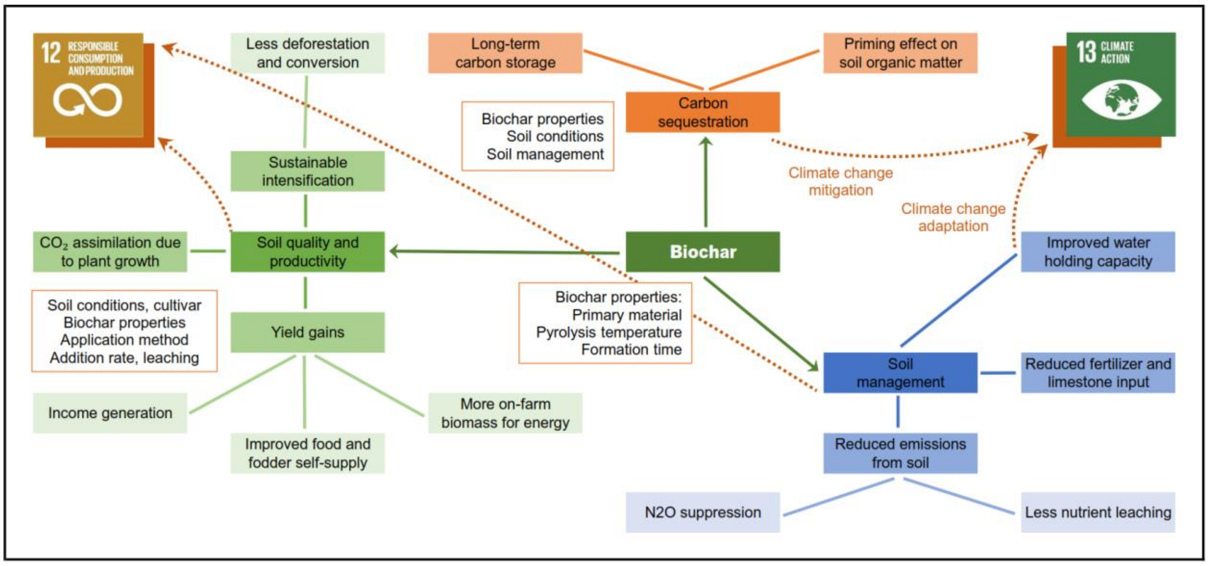


**Figure 12.** Effects of biochar application to soil

Compared to untreated crop residues that rapidly decompose, biochar is more stable. This implies that it improves soil properties over a longer period and prevents nutrient leaching into groundwater as well as emissions to the atmosphere. However, Sohi et al. (2010, pp. 67–69) point out that biochar does not only hold nutrients in a plant-available form, but may also capture or sorb toxic substances. A downturn may result from the priming effect of biochar on other soil organic matter, accelerating its decomposition and release of carbon into the atmosphere (Verheijen, Jeffery, Bastos, van der Velde, & Diafas, 2010, p. 7).

Biochar has proven especially beneficial in highly weathered tropical soils, which are characterised by a sandy texture, little organic matter, low capacities for cation exchange and available water, and acidity; in finely textured clay soils, adding labile organic matter for immediate nutrient supply might be more appropriate (Kimetu et al., 2008). Regarding crop productivity, the review highlights that the yield response depends on original soil properties, pre-existing moisture and nutrient status as well as nutrient management (Sohi et al., 2010, pp. 66–67). Whilst supplying additional nutrients, biochar foremost enhances nutrient use efficiency and retention (Sohi et al., 2010, pp. 66–71). Hence, it is most effective in combination with fertilizer, which yet may be applied at a lower rate (Kimetu et al., 2008). Lehmann and Joseph (2009, p. 6) conclude that biochar is not a suitable alternative to existing soil management, but it may render land use more sustainable.

Building on the above mentioned factors, field study results are highly sensitive to local soil and climate properties, land management, and tested crops on the one hand, and the choice of feedstock, production method, and application rate of biochar on the other hand. This implies that findings of local studies may only be transferred or generalised with caution. At the same time, it highlights the need for case specific research as implemented within the Biochar Project. Pot trials with biochar in Embu showed higher plant growth as well as reduced nutrient deficiency and drought stress (Åslund, 2012, pp. 26–30). In terms of soil properties, biochar increased soil water and carbon content, pH and cation exchange capacity (Åslund, 2012, p. 29). While soil improvement is largely supported by a similar study in Siaya (Söderberg, 2013, p. 29), the pot trials did not find corresponding gains in maize growth. Off-site experiments with different soil types and feedstocks showed that the properties of primary materials influence plant growth, but that the application rate of biochar is more important in this respect (Alvum-Toll, Karlsson, & Ström, 2011, p. 51).

Besides sustained soil amendment, the stability of biochar is decisive for climate change mitigation. Biochar has the potential to sequester carbon (i.e., store $CO_2$ in the long run; see Lehmann et al., 2006 and Lehmann et al., 2009), stabilise other organic matter (after the short-lived priming effect which spurs mineralisation), avoid fertilizer nutrient losses in the form of nitrous oxide, and indirectly prevent emissions from fertilizer production; if agricultural wastes are the primary material for carbonisation, the biochar scenario may also avoid methane emissions from natural decomposition during storage (Scholz et al., 2014, pp. 28–37; Sohi et al., 2010, pp. 70–71; Verheijen et al., 2010, pp. 6–10). In the long run, higher agricultural productivity may reduce the pressure on woodlands and conversion. This is not only due to higher availability of on-farm biomass for energy, but also due to greater crop production on existing agricultural land.

# 3 Methodological approach and data basis

This chapter links theoretical concepts of environmental assessment with the methodological approach developed for this thesis. A range of tools is available to analyse and evaluate environmental aspects of comparable systems, including Life Cycle Assessment, Material Flow Analysis and Environmental Risk Assessment (Finnveden et al., 2009). LCA is the most appropriate method for the purpose of this thesis, because it adopts a function-related view, considers both inputs (i.e., resource extractions) and outputs (i.e., services and emissions), aggregates different substances relative to their environmental impact, and avoids burden-shifting within the system (ISO, 2006a). The empirical approach reflects peculiarities of assessing a traditional bioenergy system in a developing country, and is adapted to the limited scope of the research as well as constraints in data availability. The methodological choices and assumptions are subject to comparison with relevant scientific publications in the field.

Life Cycle Assessment seeks to determine environmental aspects and potential environmental impacts occurring throughout the lifespan of a good or service (ISO, 2006a, 2006b). This means that all phases from raw material extraction, production and use until the end-of-life stage are examined, including intermediate steps of transportation or conversion. Ideally, LCA covers all aspects that might affect the natural environment, human health or natural resources as areas of protection (European Commission, 2010, p. 108; ISO, 2006a). The standards ISO 14040:2006 and ISO 14044:2006 provide guidance on how to conduct an LCA in a uniform manner. Accordingly, an LCA study comprises four phases (ISO, 2006a, 2006b):

1. Goal and scope definition
2. Life cycle inventory analysis
3. Life cycle impact assessment
4. Interpretation

The next four sections link the methodological choices of the thesis to the phases of LCA and contrast them with the provisions of the ISO standards (see ISO, 2006a, 2006b) and the International Reference Life Cycle Data System (ILCD) handbook (see European Commission, 2010). Interpreting the LCA concept narrowly, this study classifies as an “environmental system analysis using LCA methodology” as suggested by Finnveden et al. (2009), rather than as a classical LCA study.

## 3.1 Goal and scope definition

The goal and scope definition states the subject and intended use of the study and delimitates the system to be studied by system boundaries (ISO, 2006a). The aim of the first phase is to ensure a consistent study design and make methodological choices and limitations explicit. Moreover, it determines the system’s function of interest in qualitative and quantitative terms by choosing a functional unit (European Commission, 2010, p. 60; ISO, 2006a). At a later stage, the functional unit serves as a reference for the inventory data and allows to compare alternative products or scenarios on a common basis.

According to the goal and scope of the Biochar Project, this thesis assesses different options to use biomass and supply cooking energy from the perspective of an individual farm in a case study approach. See section 1.2 for an introduction to the project and section 1.3 for the goal and intended use of the present study. The case study and the three systems for comparison will be presented in more detail under chapter 4. Due to practical constraints, the scope of the research is limited to climate change as a single impact category. Figure 13 illustrates that GHG emissions are the starting point of only one of three mechanisms that determine how domestic cooking contributes to climate change. Although it is clear that particle emissions and land-cover change alter the Earth’s energy balance, their impact pathways are ambiguous and thus still excluded from current LCA methodologies (Levasseur, 2015, pp. 40–41). Besides covering a set of Kyoto greenhouse gases, this thesis adds less well-researched substances and mechanisms in a second scenario for comparison (see grey dashed frame in Figure 13). Figure 13 also highlights the two modelling steps in this thesis: first, to get from the case study to inventory results; and second, to get from the inventory to category indicator results.

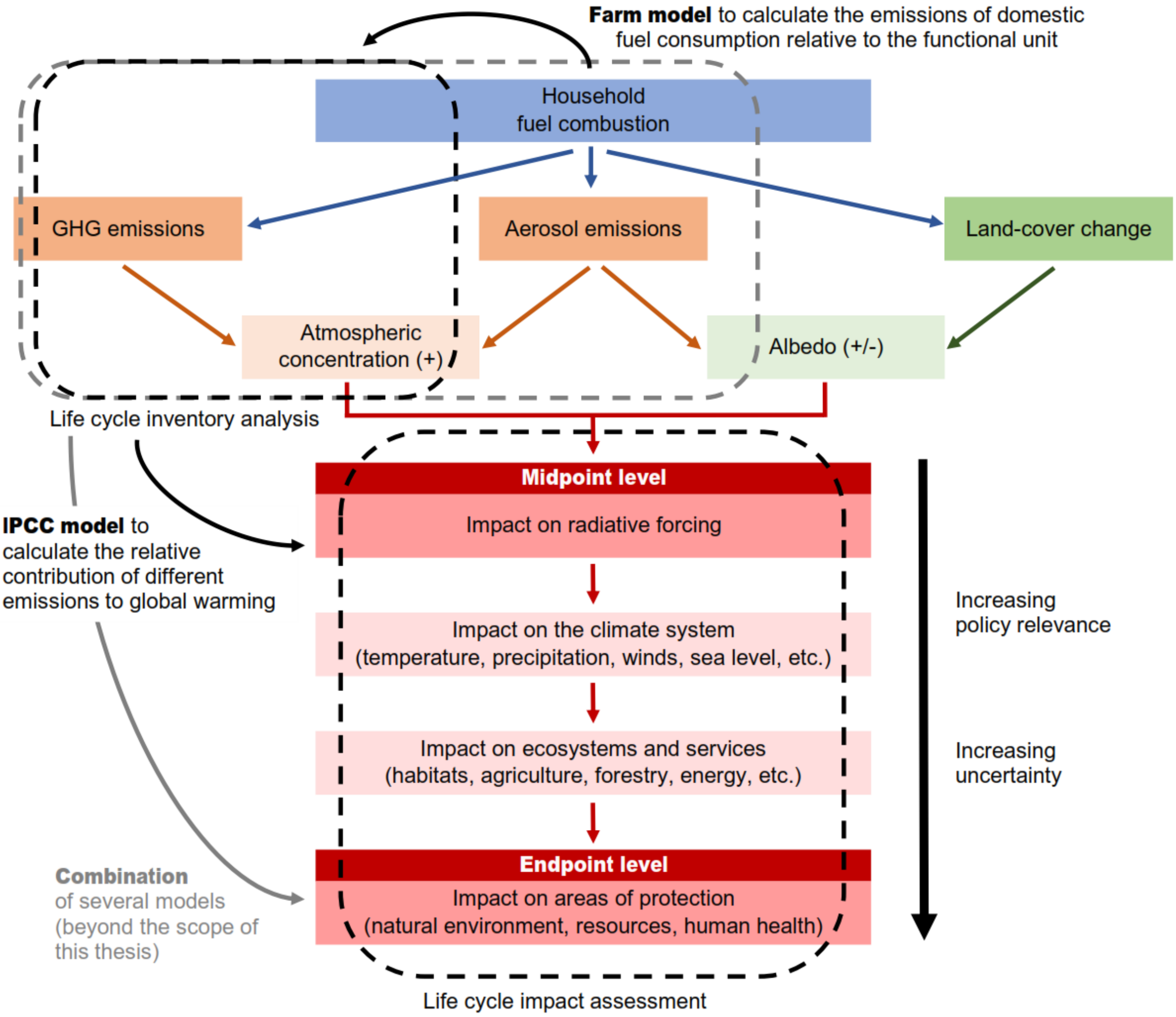


**Figure 13.** Influencing factors and impact pathway of climate change: black dashed lines indicate aspects and mechanisms that are fully or partly covered by current LCA methodologies (adapted from Fuglestvedt et al., 2003; Levasseur, 2015, p. 40)

### 3.1.1 System boundaries

The systems are built around a household's biomass consumption for domestic energy supply. Figure 14 gives an overview of the life cycle stages and main processes. The life cycle starts at raw material sourcing on-farm, off-farm or on the market. As Kenyan farmers traditionally cut fuelwood by hand and carry it home, there are no relevant impacts of harvesting or transportation. Firewood is air-dried under the sun or with off-heat from cooking in the kitchen before being used as a fuel or converted to charcoal. The central process of the use phase is fuel combustion for cooking, whereby the release of off-heat for space heating is not explicitly accounted for. Depending on the system, the conversion of wood to char takes place either upstream in the production phase (reference system) or within the use phase (charcoal and biochar system), where char is harvested as a co-product of heat for cooking. In the charcoal system, all char is resupplied to the combustion process, whereas in the biochar system, all char is applied to soil. All systems deliver ash as a solid residue of combustion, which contains a minor fraction of recalcitrant carbon.

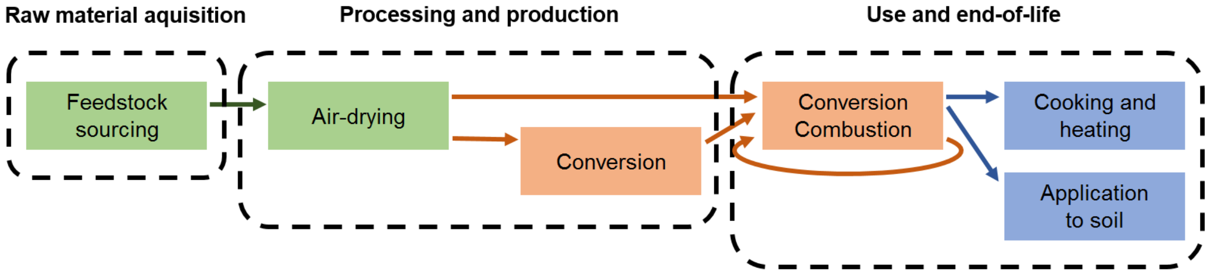


**Figure 14.** Life cycle stages and main processes covered by all three systems

The only processes that require an appliance in addition to human labour are conversion and combustion. The farmers build the traditional earth mound kiln and the three-stone stove by hand, using natural, unprocessed materials. Consequently, their construction and provision are not climate relevant. Assuming that similar to the Kenya Ceramic Jiko, the gasifier can be locally produced by artisans in the long run, transport is an insignificant process. However, both stoves are fabricated using machinery and processed materials. Therefore, the environmental impacts of construction need to be considered relative to each stove's lifetime. Apart from the fact that the KCJ is already widespread in Manyatta, it is equally included in every system and would thus not influence the comparison. In a similar assessment on char-producing cook stoves in Kenya, the authors expect that a TLUD gasifier with a lifetime of 3-5 years can be produced from 2.25 kg of locally available scrap metal (Scholz et al., 2014, pp. 80–81). Building on this assumption, the climate impact of production is minor and consequently omitted in the assessment.

Besides the technical system boundaries resulting from the processes covered in the LCA, the systems are limited to a time frame of 100 years. This boundary follows from restricting the assessment to short-term emissions in order to differentiate between labile and stabile carbon pools, or degradable and recalcitrant carbon fractions (see subsection 3.2.2).

### 3.1.2 System comparison, functional units and perspectives for modelling

In its classical sense, Life Cycle Assessment evaluates system by system, according to the respective characteristics and specific functions. In practice, LCA is also used to compare different systems regarding an identical function, with the aim to rank alternatives according to their performance and give recommendations for implementation (European Commission, 2010, p. 142). However, the more complex and realistic the systems, the less likely it is that they provide truly equivalent functions. In the case of the three options considered here, each system has some "additional benefits" that do not lie within the system boundaries. E.g., the baseline releases more off-heat with might be needed for space heating; both improved systems release less emissions detrimental to human health; and the biochar system improves soil quality and agricultural productivity. In order to avoid misleading conclusions, either the design of the systems or the interpretation of the results need to be adapted.

The following assessment only accounts for a single function, namely energy provision for cooking. The complex functions of biochar as a soil amendment are not considered in the quantitative model, since soil quality and agricultural productivity are beyond the scope of the research. If biochar is produced as a co-product of cooking, carbon sequestration improves the scenario's climate performance, but does not add an additional function. Theoretically, the two systems that do not apply char to soil could be expanded to ensure true functional equivalence. However, there are two reasons why systems expansion does not contribute to answering the research question. First, the systems are meant to represent extreme conditions, i.e., no improvement at all, 100% charcoal, or 100% biochar. Combinations along the continuum might be more likely, but blur the contrast. This is especially problematic if the system expansion technique integrates additional functions that are provided from the same feedstock basis. Since there is no conventional alternative for the function of biochar as a soil amendment available, expanding the non-biochar systems by the same product would gradually equal out the three options. Second, the amount of biomass available to farmers is limited. Hence, combining a system with high fuel consumption such as the baseline with biochar produced from the same feedstock basis is not realistic in light of limited resources. As the major service that all three systems have in common, energy provision is the only function that is quantitatively assessed, whereas the other benefits are discussed in qualitative terms.

Figure 15 gives an overview of all processes, flows and services considered in the assessment. As the flowchart illustrates, the Kenyan farm is a system with multiple inputs (i.e., fuels) and outputs (i.e., emissions, energy and soil amendments). Since the alternative systems differ both in feedstock basis and outputs to be delivered, there are two views on evaluating and optimising the climate impact throughout the life cycle.

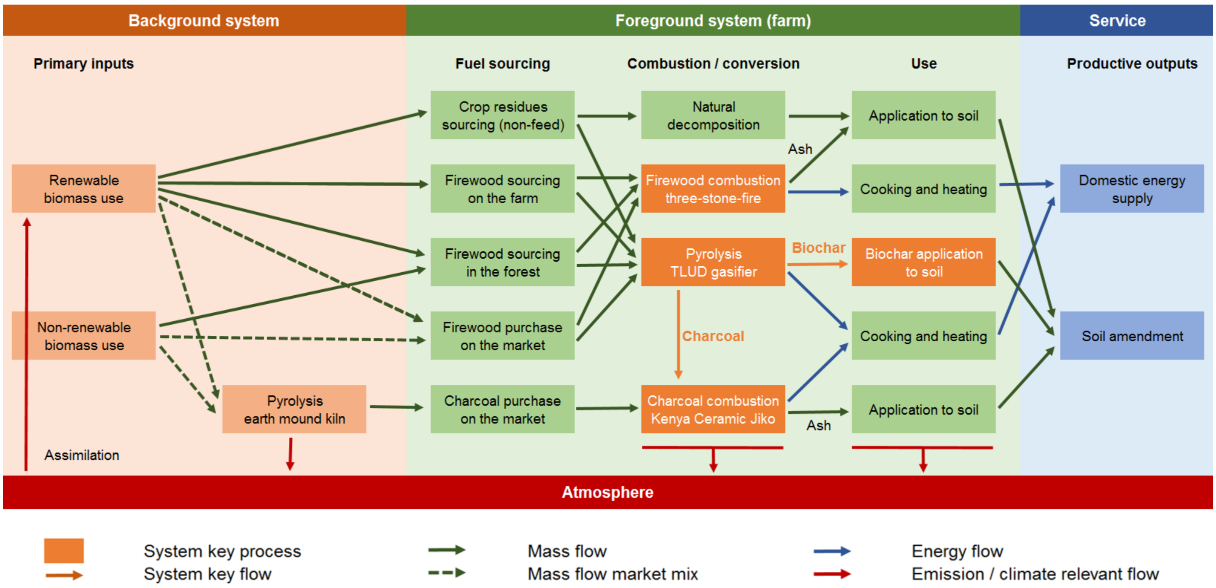


**Figure 15.** Schematic overview of processes, flows and services from all three systems

**Downstream perspective with constant fuel input.** On the input side, the resources available to a typical farm household in the case study region limit the potential supply to the system. At first, the climate impact is modelled forwards in a downstream perspective, i.e., starting from a given amount of unprocessed feedstocks available. Only if these fuels are not sufficient to meet the annual energy requirements for cooking, conventional charcoal from the market is added to the system. The downstream model employs gross fuel consumption per household and year as a functional unit, and answers the question of how different options to use available feedstocks influence the yield of services (i.e., net cooking energy and biochar) and the release of climate forcing substances.

**Upstream perspective with constant net energy supply.** On the output side, domestic energy requirements for cooking set the minimum threshold for net energy to be supplied by the system. Hence, the upstream model evaluates the climate impact backwards, starting from the household's need for cooking energy delivered to the pot. The amount of biochar to be applied as a soil amendment is not specified, since soil quality and agricultural productivity are beyond the scope of the research. The second model employs net cooking energy needs per household and year as a functional unit, and answers the question of how to optimise each system to supply the required energy at a minimal climate impact.

## 3.2 Life cycle inventory analysis

The inventory analysis identifies all relevant processes, inputs to and outputs from the system throughout its life cycle (ISO, 2006a). Raw data are collected from primary and secondary sources, converted if necessary and reported relative to the functional unit (Finnveden et al., 2009). If the inventory draws on different secondary sources, as is the case in this thesis, it is important to check and ensure coherence. Furthermore, challenges related to data quality and representativeness, variability and uncertainty need to be addressed (European Commission, 2010, pp. 122–139).

### 3.2.1 Modelling principles and framework

Modelling the system in the inventory phase comprises all steps that compile, connect and scale the data towards the functional unit (European Commission, 2010, p. 154). If a product or process provides more than one function at the same time or in succession, it is considered multifunctional; ISO 14044:2006 foresees a hierarchy of methods to deal with multifunctionality, namely subdivision, system expansion and allocation, or working with multiple reference flows if all alternatives provide the same set of functions (European Commission, 2010, p. 66; ISO, 2006b). The actual process chain analysed in this study involves multifunctional products and processes at several stages, both in the form of parallel functions (e.g., fuel combustion for cooking and heating, multiple aspects of soil improvement of biochar), and subsequent functions (i.e., biomass use for energy provision and soil amendment). However, the limitations and choices laid out above allow to bypass the need to solve multifunctionality. Since biochar for soil amendment is considered a non-mandatory service, it is not assigned any emissions from the co-production with energy and its functions in soil are not further quantified. Space heating is only a secondary reason for fuel consumption and all systems are assumed to provide sufficient off-heat; therefore, space heating is not quantified as a function either. In contrast, systems with alternative services that vary by application and mutually exclude one another, are not classified as multifunctional (European Commission, 2010, pp. 66–67). Consequently, the two options to use char (i.e., charcoal for energy provision and biochar for soil amendment) are addressed separately in two distinct systems.

The modelling principle is attributional, which means that the inventory depicts the actual or forecasted life cycle in a descriptive, static manner, with substance flows stemming from average data (European Commission, 2010, p. 71). In contrast to consequential models, attributional modelling does not account for potential structural consequences in the background system such as changes in fuel availability, consumer behaviour, market supply or prices (European Commission, 2010, p. 71). Due to the high spatial resolution of the systems, a bottom-up approach starting from individual consumption and single unit processes is most appropriate to construct the inventory. In accordance with the goal and scope definition, using site-specific data from field studies delivers more accurate, detailed and recent results than an input-output technique (Suh & Huppes, 2005). However, secondary data obtained in large-scale studies and top-down calculations from national statistics are used to fill data gaps and to check consistency.

The assessment in this thesis shall deliver a fair comparison of different systems and locally relevant results. Therefore, the first step is to establish a model farm which serves as a reference for evaluation. Instead of claiming statistical representativeness, the case study approach relies on field data from the Biochar Project whenever available and contrasts them with literature data from a larger scale to detect potential errors. Any lack of data is preferably filled from regional, Kenya specific or Eastern African sources, whereas generic data are avoided as far as possible.

As a foundation for the Biochar Project, a socio-economic baseline survey was carried out from January to February 2014, covering 152 households in the three different study areas (partly published in Mahmoud et al., forthcoming). This thesis uses the data from the 57 households interviewed in Embu County, all of them located within Manyatta Constituency[14] in the northwest of the county. After a training on the TLUD gasifier in February 2015, a second study explored details on household energy use in Kibugu, an administrative unit within Manyatta Constituency (partly published in Gitau & Njenga, 2015). Depending on the available data, this thesis uses the responses of all 41 households that participated in the training, or the responses of 20 households that received a gasifier and tested it during a two-month period.

Drawing on previous project findings, the model farm represents a typical household engaged in smallholder farming in Manyatta Constituency. Depending on the type of variable and its statistical distribution, different measures of central tendency are more appropriate to describe the middle or typical value (Fife & Mendoza, 2010, pp. 289–291). As the arithmetic average of all values in the sample, the mean is the measure of choice for a symmetrically distributed continuous variable; for skewed data, however, the median has the advantage of being less susceptible to outliers as it marks the middle point of all observations put into order; if the variable is categorical, the mode or most frequent value is the only appropriate measure for non-numerical data, whereas both median and mode can be used for ordinal categories (Fife & Mendoza, 2010, pp. 289–291). See Table 2 for an overview.

**Table 2.** Measure of choice to describe central tendency

| Variable | Variable sub-type and distribution | Measure of central tendency |
|---|---|---|
| Continuous | Interval / ratio, symmetrical | Mean |
| | Interval / ratio, skewed | Median |
| Categorical | Nominal, symmetrical / skewed | Mode |
| | Ordinal, symmetrical / skewed | Median / mode |

The survey data are analysed and processed using IBM SPSS Statistics 22 and Microsoft Excel 2013. All relevant characteristics of the model farm are documented including data sources, statistical distribution if available and calculation methods. The inventory analysis spans three modules that are relevant for the climate impact of the systems (see Figure 16):

1. **Biomass module:** quantify the primary biomass and residues available for energy purposes and biochar co-production at the farm level; differentiate between renewable and non-renewable feedstocks
2. **Products module:** characterise the available fuel types; assess the stove-fuel combinations regarding thermal energy delivered to the cooking vessel, char output and quality, and emissions
3. **Soil module:** assess the permanence of different soil organic matter (SOM) fractions regarding their potential for long-term carbon sequestration; characterise potential benefits of biochar as a soil amendment

[14] The 57 households are in the locations of Nginda (Nguviu, Gicherori, Kibugu and Ngerwe) and Kirimari (Kathangari).

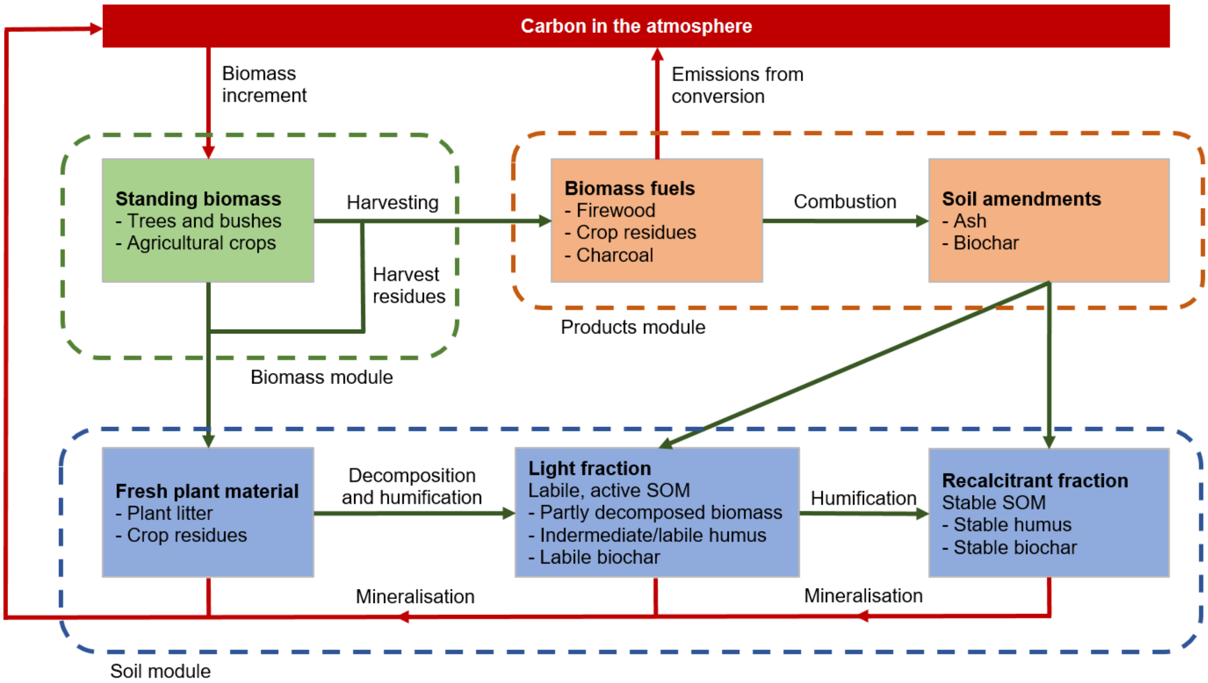


**Figure 16.** Carbon pools and carbon cycling: the colour scheme highlights the three modules at stake if the cooking practices are to be changed (adapted from Bailis et al., 2009)

### 3.2.2 Carbon accounting in bioenergy systems

As suggested by Sohi et al. (2010, pp. 74–75) and Whitman et al. (2010), this thesis takes a fate approach to carbon from available feedstocks. Consequently, the assessment considers the likely long-term fate of biomass carbon, rather than modelling intermediate pools or actual changes in total soil carbon. This way of accounting is geared to the chosen time frame of 100 years, which means that labile carbon is oxidised and released as $CO_2$ within the relevant period, whereas recalcitrant carbon remains stored. The critical parameters of this method are explained below.

**Permanence of carbon pools.** Natural decomposition and traditional biomass combustion are assumed to release all feedstock carbon within the period assessed, although it might take longer for some wood species, or if incomplete combustion leaves a recalcitrant C fraction in the ash. In the counterfactual scenarios with reduced fuel consumption, unused living carbon stocks are considered stable, which is in line with conservative methodologies for carbon accounting (Whitman et al., 2010, p. 92). In the biochar scenario, roughly half of the total biomass carbon is released during conversion; from the remaining proportion, the recalcitrant fraction is permanently sequestered whereas the labile fraction is released into the atmosphere as $CO_2$ (Lehmann et al., 2006).

**Fraction of non-renewable biomass.** Renewability determines whether the biogenic carbon emitted during combustion or sequestered in biochar is assumed to be equivalently taken up as $CO_2$ during plant regrowth. For simplicity, the fate approach neglects the time lag between the release of climate forcing pollutants to the atmosphere and $CO_2$ assimilation.

## 3.3 Life cycle impact assessment

The impact assessment models the system further along the cause-effect pathway (i.e., from emission release to damage), to evaluate the magnitude of potential environmental impacts (ISO, 2006a). The first step is to classify all substances listed in the inventory according to their potential effect on the environment; subsequently, each mass or volume flow is multiplied with a specific characterisation factor that describes a substance's relative contribution to the respective impact category (European Commission, 2010, pp. 275–277). For this purpose, the category indicator GWP expresses the radiative forcing over a chosen time horizon (commonly 100 years for long-lived and 20 years for short-lived substances), based on the measured radiative forcing and the mean atmospheric lifetime of each climate relevant pollutant (European Commission, 2015; Fuglestvedt et al., 2003; IPCC, 2013, pp. 710–712). Depending on the intended use of the study, the results can be reported as equivalent values at midpoint level, e.g., in kg $CO_2$e for the Global Warming Potential, or as damage values at endpoint level, e.g., in Disability-Adjusted Life Years for human health (European Commission, 2010, p. 276).

This thesis models the climate impact at midpoint level and relies on the latest GWP values and recommendations of the 5th Assessment Report by the Intergovernmental Panel on Climate Change (see IPCC, 2013, pp. 731–740). Appendix E summarizes the characterisation factors for two sets of emissions (i.e., well-mixed gases only, and well-mixed gases plus near-term climate forcers), primary literature sources and scaling steps. For the sake of consistency with the reference gas $CO_2$, all characterisation factors were chosen to include climate-carbon cycle feedbacks[15] as suggested by the IPCC (2013, p. 714).

As an aggregate metric, the Global Warming Commitment (GWC) is used to describe the climate change implications of each system. While the GWP weighs single species according to their potential impact, the GWC expresses the combined warming effect of a set of pollutants as emitted (Smith et al., 2000b; Smith & Haigler, 2008). With FC as the household fuel consumption, $EF_i$ as emission factor of each climate forcing gas i, and $GWP_i$ as the corresponding characterisation factor, the Global Warming Commitment is calculated as

$$GWC = FC * EF_i * GWP_i$$

The factors describing emission or conversion ratios are specific for each type of stove and feedstock used. Therefore, the GWC needs to be calculated separately for each stove-fuel combination and summed, in order to reach the final result for the model farm.

**Emission set 1.** The characterisation phase for the well-mixed gases $CO_2$, $CH_4$ and $N_2O$ is associated with low uncertainty, since their atmospheric mechanisms are well studied, and midpoint modelling is independent of exposure and regional differences (European Commission, 2010, p. 297; IPCC, 2013, p. 668; Levasseur, 2015, p. 39). The Global Warming Commitment for well-mixed GHG is calculated from fuel consumption (FC), the fraction of non-renewable biomass ($f_{NRB}$), the emission factor of each climate forcing gas i ($EF_i$) and its characterisation factor for the non-renewable and the renewable fuel fraction ($GWP_i$) as shown below. Considering that this small set of gases cannot cover the full feedstock carbon emitted, the following calculation scheme ensures that the benefit of $CO_2$ assimilation for renewable biomass is only offset for carbon emissions in the form of $CO_2$ or $CH_4$.

$$GWC_{set1} = FC * \sum_{i=1}^{n} EF_i * \left[f_{NRB} * GWP_{NRB,i} + (1 - f_{NRB}) * GWP_{RB,i}\right]$$

**Emission set 2.** Following the approach of Grieshop et al. (2011), five near-term climate forcers are added in a second GWC model that aims to better estimate the full climate impact (IPCC, 2013, p. 668). Therefore, the characterisation factors were chosen to cover direct and

[15] Climate-carbon cycle feedbacks refer to interactions between the atmospheric $CO_2$ concentration, temperature change and natural carbon storage. Since the 4th Assessment Report of the IPCC (2007, p. 69), the factors for GWP partly reflect that global warming is likely to reduce the uptake and permanent storage of carbon by land and ocean sinks.

indirect[16] effects for global warming as completely as possible. Whilst providing a valuable basis for comparison, the extended set of emissions involves considerably higher uncertainties, because CO, NMHCs, particulate matter (i.e., black carbon and organic carbon particles) and the aerosol precursor $SO_2$ are short-lived, not well-mixed and poorly understood in their effects on radiative forcing (Bailis et al., 2003; Grieshop et al., 2011). Moreover, only a limited fraction of aerosols from indoor combustion reach ambient air at all, since particulate matter is largely deposited on the roof and walls of dwellings (Bailis et al., 2003). The Global Warming Commitment of the second set is calculated only from the characterisation factors for non-renewable biomass. The feedstock carbon emitted ($C_{em}$) is calculated from the total carbon content per kg fuel by subtracting the carbon-based conversion factor from raw biomass to char, brads, liquids and ash. After transforming the carbon emitted to $CO_2$ according to its mass fraction of 27.29% (corresponding to the factor of 3.66), it can be subtracted as a whole to account for $CO_2$ uptake during plant regrowth for the renewable fraction ($1 - f_{NRB}$). Since the second set of pollutants is supposed to cover all carbon emitted, this approach is expected to be more accurate than adapting each characterisation factor for the renewable fraction.

$$GWC_{set2} = FC * \left[\sum_{i=1}^{n} EF_i * GWP_{NRB,i} - C_{em} * 3.66 * (1 - f_{NRB})\right]$$

The Global Warming Potential integrates radiative forcing due to a pulse emission over time, and sets it in relation to the corresponding value for $CO_2$ (IPCC, 2013, p. 710). Therefore, the metric is highly sensitive to the atmospheric lifetime of the substance addressed, both in relation to the selected time frame and the lifetime of the reference gas $CO_2$. When climate forcing agents with different lifetimes are jointly assessed, the time horizon implicitly leads to a weighting of (a) near and long-term climate impacts, and (b) the relevance of short- and long-lived pollutants for mitigation efforts (Fuglestvedt et al., 2003, pp. 292–293; IPCC, 2013, pp. 711–712). Therefore, Fuglestvedt et al. (2003, pp. 292–293) point out that the choice of time horizon should reflect the interest in either abrupt near-term effects and the rate of temperature change (20-50 years), or long-term risks and the eventual full magnitude of temperature change (100-500 years).

Besides the fact that $GWP_{100}$ is an institutionally established metric (not least since the Kyoto Protocol) and thus most suitable for comparisons with other studies, this thesis aims to capture full climate impacts in a long-term perspective. Initially, these considerations made 100 years the time frame of choice. However, $GWP_{100}$ leads to a misrepresentation of short-lived climate forcers (Fuglestvedt et al., 2003, p. 270; Grieshop et al., 2011). Especially in the second set of emissions, it hampers the attempt to model the problematic effects of open biofuel combustion in a more comprehensive manner. Therefore, a 20-year time horizon is used for comparison, which is also in line with some previous studies in the field (Bailis et al., 2003; Smith et al., 2000a; Smith et al., 2000b).

Irrespective of substances and time frame considered, the biochar system requires extending the GWC model for the partial sequestration of carbon in soil (i.e., the fraction of recalcitrant carbon $f_{RC}$), and the release of the remaining fraction of labile carbon ($1 - f_{RC}$) as $CO_2$. The release of carbon from the renewable fraction and the storage of carbon from the non-renewable fraction have no net climate impact and can thus be left out. However, the release of carbon from the non-renewable fraction has a positive net climate impact and is calculated as $f_{NRB} * (1 - f_{RC})$. Conversely, the storage of carbon from the renewable fraction has a negative

[16] Substances emitted into the atmosphere may directly cause radiative forcing due to their own properties, or indirectly by altering the concentration of other climate forcers (Fuglestvedt et al., 2003). In the context of particles, direct aerosol effects refer to the absorption or reflection of solar radiation, and indirect effects to aerosol induced changes in cloud albedo (Levasseur, 2015, p. 40).

net climate impact and is calculated as $(1 - f_{NRB}) * f_{RC}$. Starting from the feedstock consumption FC, this is calculated from the share of carbon not emitted during conversion ($1-C_{em}$) and the scaling factor from elementary carbon to $CO_2$.

$$GWC_{bc} = FC * (1 - C_{em}) * 3.66 * [f_{NRB} * (1 - f_{RC}) - (1 - f_{NRB}) * f_{RC}]$$

The model is implemented in Microsoft Excel 2013 to calculate feedstock consumption, services (i.e., cooking energy and biochar) and pollutant emissions. Using the equations presented above, it determines the climate impact for different pollutant sets and timeframes. The first data sheet allows to vary the following parameters:

- the total consumption of each fuel type;
- the fraction of non-renewable biomass per feedstock species on-farm or off-farm;
- the shares of on-farm and off-farm sourcing;
- the shares of collection and purchase on the market; and
- the recalcitrant fraction of biochar.

The performance indicators and emission factors of each stove-fuel combination may be altered as well, but it is up to the user to ensure consistency with characteristics of the respective combustion process, the fuel's chemical composition and the share of total feedstock carbon. A third sheet summarizes the characterisation factors for each gas depending on time frame and renewability. Any factor may be adapted to the latest findings, which is especially relevant regarding short-lived climate forcers. The inventory data and results of the impact assessment are processed and analysed using pivot tables that allow to break down the impact per system, per stove-fuel combination, per set of gases, per gas and per time frame.

## 3.4 Interpretation

The interpretation summarizes and critically evaluates the results from the preceding LCA phases (ISO, 2006a). Besides drawing conclusions according to the goal and scope of the study, the aim is to ensure the quality of the assessment by checking for completeness, sensitivity, and consistency (European Commission, 2010, p. 71). Ultimately, the interpretation phase provides feedback to improve previous LCA steps and forms the basis for recommendations and decision-making.

Uncertainty inevitably increases in the course of conducting a Life Cycle Assessment. In order to optimise the robustness and relevance of the results, it is important to be aware of the types and sources of uncertainty (European Commission, 2010, pp. 377–378):

1. Methodological choices: system boundaries, functional unit, modelling principles and approach, choice of impact categories, time horizon, etc.
2. Assumptions made to construct the systems: representativeness of the chosen processes and relevance for the case study
3. Process data used in the inventory analysis (first modelling step): feedstock properties, conversion factors, stove efficiency, emission factors, etc.
4. Assessment data used in the impact assessment (second modelling step): characterisation factors

The variation due to methodological choices and assumptions (see 1 and 2) is discrete, because it issues from a finite number of options; according to the European Commission (2010, p. 378), the resulting uncertainty is best addressed in distinct systems (i.e., baseline, charcoal and biochar system), and different scenarios for each of them (i.e., different modelling perspectives and related functional units; well-mixed GHG and extended set of substances, time horizon of 20 and 100 years).

The stochastic uncertainty of process data (see 3) and assessment data (see 4) can be described by statistical measures including mean, standard deviation and distribution type (European Commission, 2010, p. 378). Based on descriptive statistics, Finnveden et al. (2009) present a variety of tools to address uncertainty, including Monte Carlo simulation, fuzzy set theory or classical tests of hypothesis. In the inventory of this thesis, some parameters draw on very small sample sizes (mainly owing to the case study approach) or completely lack descriptive statistics (if not accessible for external secondary data). Under these circumstances, a pragmatic solution to deal with uncertainty is to identify key processes, factors and choices and to handle their realistic lower and upper boundary as discrete options for parameter variation (European Commission, 2010, p. 380; Finnveden et al., 2009). The resulting set of what-if calculations provides benchmarks to evaluate the results under default settings and to discuss their robustness.

The opportunity to test different assumptions, vary parameters and combine various settings without the need to recalculate the results is one of the key features of the model as implemented in Excel:

- A data sheet for parameter variation allows to adapt single values;
- the scenario manager includes four settings to test different shares of non-renewable biomass (as implemented in the downstream model);
- the goal seek helps to adapt fuel consumption to a desired net energy supply (as implemented in the upstream model)
- separate sheets offer three levels of analysis, i.e., systems, stove-fuel combinations and process chains;
- filters allow to switch between pollutant sets and time frames; and
- pivot tables can display the results in sums or break them down into systems, stove-fuel combinations, process chains and pollutant species.

# 4 Case and system description

After an introduction to the characteristics of the model farm, the following sections break down the overview of all alternatives (see Figure 15) into three separate systems. The baseline and the two systems for improved feedstock management are designed to represent extreme cases. In order not to blur the differences, each system is limited certain stove types and use options while maintaining reasonable combinations. The parameter description of the reference system (baseline) is valid for all alternatives, unless differences are explicitly stated for the charcoal and the biochar system. Appendix D lists the main inventory data for all systems.

## 4.1 Characteristics of the model farm

The model farm reflects the characteristics of a household engaged in smallholder farming in Manyatta Constituency in the northwest of Embu County. Located at the south eastern slope of Mount Kenya, Embu County covers a high variety of agro-ecological zones shaped by altitude, temperature and rainfall patterns (Jaetzold, Smidt, Hornet, & Shisanya, 2006, p. 22). The case study region in Manyatta Constituency extends over the lower highlands and upper midlands, characterised by 1,000-2,000 mm annual precipitation and mean annual temperatures between 16 and 21°C; these conditions particularly favour tea and coffee production as major cash crops, but are also suitable for maize and other crops (Jaetzold et al., 2006, pp. 9–31).

The model farm has 5 household members (corresponding to 3.6 standard adults[17]) and 0.95 hectares of agricultural land. Farming is the main occupation, forming the basis for income generation, food and energy supply. Traditionally, manure from livestock, and crop residues are used to restore soil organic carbon and nutrients. Limestone is widely used to increase the pH of acidic soils. Situated in a high potential zone for agricultural production, the model farm grows a comparatively high proportion of crops for sale on the market. Mainly related to cash crop production, the household additionally applies mineral fertilizers worth roughly 15.000 Kenyan Shillings[18] per year.

## 4.2 Reference system (baseline): current practices

The reference system reflects the current cooking practices regarding feedstock management, fuel consumption, stove technology and the use of combustion residues. The flowchart in Figure 17 gives an overview of the processes, flows and contributions to services considered in the assessment. In order to keep the system simple, marginal feedstocks or options to use them are left out, e.g. other tree species and crops, on-farm charcoal production as well as the use of ashes from cooking as a soil amendment. Here, the term “marginal” refers either to a minor share in the total consumption per farm or a minor share of farms using the option at all. Hence, none of the omitted variables is likely to significantly alter the results.

[17] Suggested for Kitchen Performance Tests by Bailis, Smith, and Edwards (2007, p. 17); “standard adult” equivalence factors developed for FAO wood fuel surveys: children at the age of 0-14 are weighted at 0.5, women from 15 at 0.8, men at the age of 15-59 at 1.0, and men from 60 at 0.8 (FAO and WHO, 1973 cited in Bailis et al., 2007, p. 17); in this thesis, the weighting had to be adapted to the limited data availability, resulting in the following factors for male and female household members: 0-5 years at 0.5, 6-18 years at 0.6, 19-55 years at 0.9, and from 56 years at 0.8; this is similar to the approach of Torres-Rojas et al. (2011), who use factors of 0.5 for children and 0.9 for adults

[18] 1 Kenyan Shilling = 0.008972 Euro (conversion rate per January 2016); hence, the expenditures for inorganic fertilizer correspond to roughly 136 Euro per household and year.

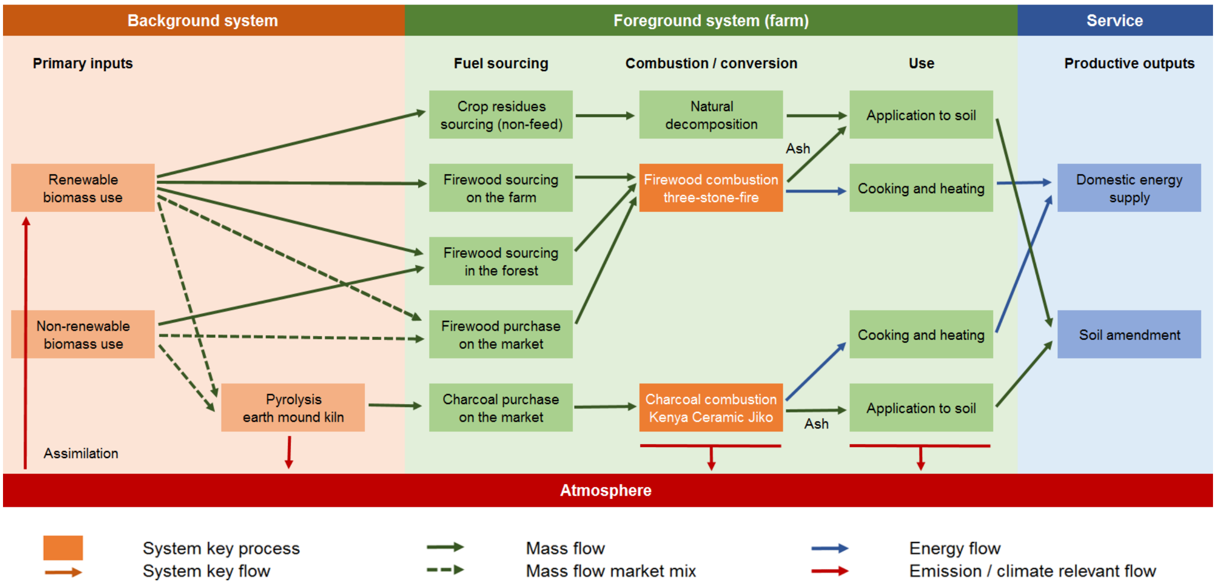


**Figure 17.** Reference system (baseline): current cooking practices with three-stone stove and Kenya Ceramic Jiko

**Cook stoves and kilns.** Cooking takes place inside of an unvented dwelling, which provides room for the kitchen and accommodates all family members. As the vast majority of rural households in Kenya, the model farm uses a three-stone stove for cooking and space heating, fuelled with firewood and farm residues. For charcoal combustion, the Kenya Ceramic Jiko is widespread in Manyatta and used in combination with the three-stone stove. Whilst the household obtains most firewood for free, i.e., either collected on the farm premises or on wooded land nearby, it is common to buy charcoal on the local market. Conventional charcoal from small-scale production is converted in traditional earth mound kilns (Mutimba & Barasa, 2005, p. 12). The thermal efficiencies chosen as a basis for the assessment, i.e. 15% for the three-stone stove with firewood, and 30% for the KCJ with conventional charcoal, are derived from literature as summarised in Table 1 (see subsection 2.4.1).

**Feedstocks and biomass supply.** Firewood is the principal fuel, while the remaining demand is covered by charcoal and agricultural residues. In the lower highlands and upper midlands, farmers plant trees for fuelwood along boundaries, dispersed in cropland as well as in woodlots, where fast growing species are most common. The model farm has its own woodlot and supplies 69% of its demand for wood from farm sources, most notably from *Grevillea robusta* and Eucalyptus trees, as well as coffee shrubs. Another 16% of the fuelwood is collected off-farm. While on-farm wood is sustainably harvested, only 57% of the proportion sourced in nearby forests and woodlands is renewable (Drigo et al., 2015, p. 26).

The model farm buys the remaining 15% on the local market. Firewood on the market is supplied from local farmers and hence considered to have the same on-farm and off-farm proportions as wood collected by the model farm itself (i.e., 81:19). According to a report on Kenya's charcoal sector, small-scale charcoal producers in high potential areas mainly convert off-cuts and remnants from farm trees into charcoal (Mutimba & Barasa, 2005, pp. 12–13). Overall, this justifies to assume an identical share of non-renewable biomass in collected and bought firewood as well as charcoal from the market.

To estimate the supply potential it is important to consider that the availability of feedstocks for energy varies with growing seasons and is restricted by alternative uses for animal feed, soil protection against erosion, nutrient recycling or construction (Torres-Rojas et al., 2011). For simplicity, maize cobs are the only farm residues considered in this assessment, since the use of other organic materials such as crop stalks and leaves or animal dung conflicts with other functions. This is in line with findings from Kituyi et al. (2001a), showing that maize cobs are the most common crop residue type used for energy purposes. Prunings from coffee shrubs are not classified as crop residues; due to similar properties and a lack of data, they are included in the on-farm firewood fraction.

**Fuel use and energy consumption.** Domestic fuel use depends on various factors related to feedstock sourcing (e.g., fuel availability, cost and source distance), consumption (e.g., household size and settings, climate, season, cooking habits and duration), as well as stove type and efficiency (Kituyi et al., 2001a). This leads to values for household energy demand that differ by up to one order of magnitude (Grieshop et al., 2011). Besides these factors, differences in the methods of sampling, data collection, data processing and reporting hamper the comparability of literature sources. Examples from the studies reviewed include differentiation between agro-ecological zones or rural and urban areas; study duration and consideration of seasonal fluctuations; data collection by interviews or measurements; definition of household size (by number of people or standard adult equivalents relative to age and gender); parameterisation of moisture and energy content, conversion factors and efficiency; and reporting in terms of primary feedstock weight (dry, air-dry or wet), gross fuel weight, gross energy consumption or net energy delivered to the cooking vessel (see Grieshop et al., 2011; Kituyi et al., 2001b; Kituyi et al., 2001a; MoE, 2002; Scholz et al., 2014; Torres-Rojas et al., 2011; Whitman et al., 2011; Whitman et al., 2010).

For Western Kenya, Whitman et al. (2011) report an average annual consumption of bone dry firewood of 712 kg/capita in households with 6.7 adult equivalents (sample range between 365 and 1,095 kg/capita). Scaling this value for the model household results in 2,562 kg/hh. For Western Kenyan households with 8.14 family members or 5.7 adult equivalents, Torres-Rojas et al. (2011) calculate an average annual cooking energy consumption of 10.5 GJ/capita with traditional wood fuel stoves (sample range between 4.5 and 21.1 GJ/capita). This corresponds to 610 kg bone dry fuelwood per capita or scaled for the model household, 2,198 kg/hh. However, the fact that the model household is considerably smaller, located in a high potential agricultural zone and facing a colder climate justifies higher rather than lower values (Kituyi et al., 2001b; Kituyi et al., 2001a).

In a first approach, the model household's annual fuel consumption is determined based on data from the Biochar Project. However, the resulting proportions of 2,040 kg of firewood as collected (i.e., not accounting for considerable weight losses during drying[19]) and 190 kg of charcoal are very low compared to other studies. The values are derived from a strongly skewed sample with a large range between minimum and maximum values. Moreover, a questionnaire survey does not provide a robust basis to estimate fuel consumption[20]. Therefore, the data from a country wide study combining questionnaires and measurements are used (see Kituyi et al., 2001b; Kituyi et al., 2001a). The study aimed to estimate the total domestic consumption levels of biofuels in Kenya and thus not only includes fuel combustion for cooking, but also for space heating and lighting. However, the study was carried out in the dry season when only households in high altitude regions need extra fuel for heating (Kituyi et al., 2001b). In order to avoid the data to be biased by additional fuel consumption for heating, country-wide averages are used to estimate the model farm's fuel use. Scaled from a household size of 5.5 to 5 people, this results in annual consumption levels of 3,900 kg of air-

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[19] The moisture content of fuelwood depends on the initial properties of the feedstock, drying time and conditions, the ambient temperature and relative humidity; according to FAO (1983, s.p.), freshly cut wood can have up to 100% moisture on a dry basis (Md), and air-dried cooking fuel 10-20%. For consistency between literature and project data, all air-dried firewood is assumed at 11% Md. Typical moisture contents of air-dried maize cobs are reported in a similar range (UN, 1987, p. 36).

[20] The values are calculated as the median from the household heads' personal estimates on the household's monthly consumption of (a) fuelwood in woman's loads (given in 4 categories) and the average weight per woman's load; and (b) charcoal in kasuku (given in 5 categories) and the average weight per kasuku of conventional charcoal.

dry firewood at 11% moisture on a dry basis (Md); 475 kg of charcoal at 5% Md; and 150 kg of air-dry maize cobs at 10% moisture on a dry basis (considering that they are only available during 3 months of the year). The country-wide values (see Kituyi et al., 2001b) are slightly lower than those for the high altitude zone, but considerably higher than those for dry zones (see Kituyi et al., 2001a). Consequently, it seems reasonable to assume that the average figures represent cooking energy consumption in Manyatta well, and are free from overestimation due to heating or underestimation due to fuel scarcity in dry regions.

The project surveys suggest that in Manyatta, maize cobs rather support lighting the fire than substituting for fuelwood. Due to a lack of more precise data, maize cobs are assumed to be consumed during the lighting process or left for natural decomposition in the baseline system. In either way, they do not contribute to fuel supply and are oxidised under aerobic conditions. Table 3 summarises the results of each calculation step from fuel consumption to net energy delivered to the cooking vessel. The factors for thermal efficiency account for both combustion efficiency and heat transfer efficiency to the pot. Net energy consumption ($EC_{net}$) is calculated from the fuel consumption of the charcoal fraction ($FC_c$) and each woody biomass fraction ($FC_b$), the corresponding lower heating value (LHV) and the thermal efficiencies of the stove-fuel combinations ($\eta_{3stone}$ for firewood and $\eta_{KCJ}$ for charcoal) as

$$Baseline\ EC_{net} = \eta_{KCJ} * FC_c * LHV_c + \eta_{3stone} * \sum_{b=1}^{n} FC_b * LHV_b$$

**Table 3.** Annual biomass supply for cooking: fuel consumption at the given moisture content on a dry basis (Md); gross energy consumption from different feedstocks depending on lower heating values; net energy consumption from different fuels fractions depending on thermal efficiencies

| Feedstock | Fuel [kg/hh*a] | Md [%] | LHV [MJ/kg] | Gross energy [GJ/hh*a] | Efficiency [%] | Net energy [GJ/hh*a] |
|---|---|---|---|---|---|---|
| Firewood | 3,900 | | | 64.6 | | 9.7 |
| Collected on-farm (69%) | 2,690 | | | | | |
| Eucalyptus (34.5%) | 1,345 | 10.7 | 15.3 | 20.6 | 15% | 3.1 |
| Grevillea (34.5%) | 1,345 | 10.7 | 17.7 | 23.8 | 15% | 3.6 |
| Collected off-farm (16%) | 625 | 10.7 | 16.7 | 10.4 | 15% | 1.6 |
| Bought (15%) | | | | | | |
| On-farm (12.15%) | 475 | 10.7 | 16.5 | 7.8 | 15% | 1.2 |
| Off-farm (2.85%) | 110 | 10.7 | 16.7 | 1.8 | 15% | 0.3 |
| Maize cobs | | | | | | |
| Collected on-farm | 750 | 9.9 | 17.2 | 12.9 | 0% | 0.0 |
| Charcoal | | | | | | |
| Bought | 475 | 4.8 | 30.8 | 14.6 | 30% | 4.4 |
| Conversion loss | - | - | - | 14.9 | - | - |
| Total | | | | 108.0 | | 14.1 |

The lower heating values draw on a laboratory analysis of untreated biomass and charcoal samples from the Biochar Project, conducted at the Kenya Forestry Research Institute (KEFRI) on behalf of ICRAF. The data for *Grevillea robusta* prunings and maize cobs are scaled to a higher moisture content (i.e., 15% Md), in order to better represent the average properties of air-dried resources at the model farm. Secondary data are used for comparison, and to fill data gaps for off-farm wood and conventional charcoal.

**Stove and kiln emissions.** The emissions from combustion and conversion are determined based on published data from cooking tests and models using carbon mass balances (see Appendix D for the figures and sources). The carbon balance method is based on the premise that during combustion, the total carbon content of the fuel (TC) is converted to gases ($CO_2$, $CH_4$, CO, NMHCs), particulate matter (BC and OC) and solid residues (ash or char), and has been used in most studies reviewed (see, i.a., Bailis et al., 2003; Pennise et al., 2001; Smith et al., 2000a; Sparrevik, Adam, Martinsen, Jubaedah, & Cornelissen, 2015):

$$TC = C_{CO2} + C_{CH4} + C_{CO} + C_{NMHC} + BC + OC + C_{ash} + C_{char}$$

The fractions of species emitted are both fuel and stove specific: the higher the fuel's carbon content, the higher the release of carbonaceous pollutants; the cleaner and more efficient the combustion process, the higher the share of carbon emitted as $CO_2$. With the exception of solid residues, any carbon that is not fully oxidised is converted into products of incomplete combustion (PIC), thereby lowering the energy yield and increasing the climate impact. This is expressed in the so-called K-factor, the ratio of PIC to $CO_2$, and the nominal combustion efficiency (NCE) as its counterpart (Smith et al., 2000a, p. 14):

$$TC - C_{ash} - C_{char} = C_{CO2} + PIC$$

$$K = \frac{C_{CH4} + C_{CO} + C_{NMHC} + BC + OC}{CO_2}$$

$$NCE = \frac{CO_2}{PIC + CO_2} = 1 + \frac{1}{K}$$

The emission factors are reported as pollutant mass per kg of dry fuel for each stove-fuel combination. For the use of *Grevillea robusta* in the three-stone stove, emission factors for Eucalyptus are used and scaled to the higher carbon content per kg dry fuel. Since the elementary composition of the two tropical hardwood species is similar in relation to carbon (see Jain, 1999 for *Grevillea robusta* and Smith et al., 2000a, p. 70 for Eucalyptus), this approximation is not expected to cause a critical error. However, *Grevillea robusta* has an exceptionally high energy content, which is probably not representative for all wood species collected on-farm. Therefore, on-farm wood is assumed to behave like *Grevillea robusta* and Eucalyptus in equal proportions of 50% each. For off-farm wood, Acacia is chosen as a reference species with emission factors from Bailis et al. (2003). It is among the dominant species of Kenya's woodland and shrubland vegetation and a dominant source of fuelwood throughout the country (Kigomo, 2001, pp. 6–7). Biodegradation of maize cobs is treated equally to stove-fuel combinations, with all carbon being released as $CO_2$.

Aerosols are commonly reported as total suspended particles (TSP on a pollutant mass basis; TSPC on a carbon mass basis), or as particulate matter below a certain diameter (e.g., $PM_{10}$ or $PM_{2.5}$). Both are metrics for the sum of black carbon and organic matter (OM), which consists of organic carbon plus other elements. If not given on a carbon basis, a conversion factor from OM to OC of 2.1 is applied as suggested specifically for fireplace combustion of Eucalyptus wood, and as an average for non-urban aerosols (Turpin & Lim, 2001). The emission factors of black and organic carbon are calculated using typical ratios for wood burning cook stoves, namely EC/TSPC = 0.30 and OC/TSPC = 0.70, with all values on a carbon mass basis (Roden, Bond, Conway, & Pinel, 2006). The figures show that the incomplete combustion of biomass forms a larger fraction of organic than black carbon, which is opposite for fossil fuels. While attempts to increase efficiency are likely to lower TSP emissions, they increase the EC/TSPC ratio (Bond et al., 2004).

As the release of pollutant species depends on the stage of combustion (i.e., lighting, flaming and smouldering fire), the emission factors are drawn from studies that either measured ultimate emissions (e.g., Smith et al., 2000a), or accounted for the duration of each phase (e.g., Bailis et al., 2003). The conversion of wood to charcoal is assessed separately with emission factors from Pennise et al. (2001), expressed per kg of charcoal produced from Eucalyptus and Acacia species in traditional earth mound kilns. Emission factors from Bailis et al. (2003) characterise the subsequent combustion in the Kenya Ceramic Jiko. For better comparability, the factors of both stages are converted to emissions per kg bone-dry charcoal. Based on Bond et al. (2004), the ratios of EC and OC to TSPC are estimated at 0.13 and 0.87, respectively, for charcoal production, and 0.43 and 0.57, respectively, for charcoal combustion.

Due to a lack of measurement data for the relevant wood species, emissions of sulphur dioxide are calculated from each fuel's sulphur content (see Smith et al., 2000a, p. 70), assuming that sulphur is entirely oxidised to $SO_2$. In the case of pyrolysis, the data suggest that sulphur is largely stored in the char and mainly released during combustion. Accordingly, the production and consumption of 1 kg of charcoal emit estimated shares of 20% and 80% of the feedstock's sulphur content, respectively. The resulting emission factors lie well within the ranges for biofuel combustion reviewed by Gadi, Kulshrestha, Sarkar, Garg, and Parashar (2003).

## 4.3 Improved systems

The charcoal and the biochar system replace the open three-stone stove by a closed TLUD gasifier. During the test period in Manyatta, maize cobs proved to be a valuable feedstock for the gasifier and are thus considered as an additional input material. As a co-product of the carbonisation process, the gasifier provides thermal energy for cooking and heating. Appendix D provides the inventory data for both improved systems.

**Thermal efficiency and conversion in the TLUD gasifier.** A pyrolytic cook stove serves two purposes at the same time, namely (1) delivering thermal energy to the cooking pot; and (2) recovering energy in char. Consequently, there are two measures of efficiency that apply, and to some extent increasing one limits the other: whilst thermal efficiency rises proportionally to complete combustion of carbon compounds to $CO_2$, the relationship is inverse for conversion efficiency, aiming to store carbon in solid char. This trade-off suggests that the relationship of the two measures depends less on stove design than on the purpose of the user and the mode of operation. Whilst laboratory tests comparing different stoves tend to optimise the operation regarding one primary function (which is commonly either energy delivered or biochar production), this is not the case when the stoves are used at the household level. Moreover, combining data from different tests involves the risk to over-estimate the full energy potential of the primary feedstock.

These reasons speak for using local field study data from cooking tests as a basis to determine thermal efficiency and conversion ratios. The measurements in five households were conducted for the three-stone stove with *Grevillea robusta* prunings, and for the TLUD gasifier with *Grevillea robusta* prunings and maize cobs, respectively. The data for *Grevillea robusta* are used as a calculation basis for any woody biomass considered in this assessment. During the cooking tests, the energy delivered to the vessel was not measured directly, but can be determined in relation to the three-stone stove, assuming its thermal efficiency at 15% (Kaygusuz, 2011; MoE, 2002, p. 91; UN, 1987, p. 50). For the TLUD gasifier, the resulting thermal efficiencies are 21% with wood fuels, and 19% with maize cobs. It is important to note that in this context, thermal efficiency omits the energy stored in char, which will be only accounted for in the combustion phase of the charcoal system. Thermal efficiency is calculated as the ratio of energy delivered to the cooking pot to gross fuel energy input:

$$\eta_{TLUD} = \frac{\mathrm{EC}_{net}}{FC_b * LHV_b}$$

where $EC_{net}$ is net energy consumption, $FC_b$ is the fuel consumption of biomass fraction b and $LHV_b$ its corresponding lower heating value.

For comparisons with other stoves, a second efficiency measure is interesting that subtracts the energy content of the char fraction from gross fuel energy consumption:

$$\eta'_{TLUD} = \frac{\mathrm{EC}_{net}}{FC_b * LHV_b - m_b * FC_b * LHV_{bc}}$$

Here, the energy content of char is calculated using a mass-based conversion factor from raw biomass type b to char ($m_b$), and the lower heating value of the corresponding char ($LHV_{bc}$). The char-corrected efficiency of the gasifier is 29% with wood fuels, and 27% with maize cobs. Compared to other studies reporting 42% for both wood pellets and maize cobs (see Huangfu et al., 2014; Tryner, Willson, & Marchese, 2014), these values are low. However, both assessments were conducted in laboratory settings, which is likely to be associated with better process management than everyday cooking activities in the field.

The char samples from the project were analysed in terms of energy content (lower heating values on a wet mass basis of 24.7 MJ/kg for *Grevillea robusta* char and 26.4 MJ/kg for maize cob char), but not in terms of carbon content. Yet, the carbon content alters the emission factors of pyrolysis and combustion, as well as the potential for carbon sequestration in the biochar system. An evaluation of established correlations between the higher heating value (HHV) and proximate or ultimate analysis data of biomass fuels showed that simple equations may already provide high accuracy, relying on the high correlation of HHV and carbon content (Sheng & Azevedo, 2005). The refined relationship from Sheng and Azevedo (2005) is used for a first estimate of the carbon content:

$$HHV = 0.3259 * \mathrm{C} + 3.4597$$

However, project and literature data suggest that *Grevillea robusta* has the lowest heating value in relation to its high carbon content, which is mainly due to the large ash fraction (Jain, 1999). While Eucalyptus wood is intermediate in this regard, Acacia wood has the best fuel properties. As the non-combustible fraction, the feedstock's ash content is transferred into char, where it is enriched in the course of mass loss. Therefore, it is likely that the energy to carbon ratio is also lowest for *Grevillea robusta* char. In contrast to ash, the carbon content of the feedstock is a poor basis to estimate a biochar's carbon content, as its recovery largely depends on chemical compounds and pyrolysis conditions including temperature, time, moisture and pressure (Antal et al., 1996; Enders, Hanley, Whitman, Joseph, & Lehmann, 2012). Data from the Phyllis database show that char from tropical hardwood typically has a carbon content of 70-80% on a dry basis (ECN, 2016), with values for Eucalyptus wood (Gaur & Reed, 1995) and *Gmelina arborea* (serving as a substitute for Acacia due to similar properties; Fuwape & Akindele, 1997) falling well within that range. For the sake of simplicity, all wood chars from the TLUD gasifier are assumed at 7.2% Md, and 75.6% carbon content on a dry basis. The LHVs for Eucalyptus and Acacia char are obtained from the same datasets. In order to avoid distortion, the char yield needs to be lower for Eucalyptus and Acacia. After holding thermal efficiency constant for all wood species, the same should apply to conversion efficiencies, i.e. the share of gross feedstock energy stored in char[21]:

$$\eta_{char} = \frac{m_b * LHV_{bc}}{LHV_b}$$

This assumption allows to estimate the charcoal yield for Eucalyptus and Acacia based on the principle of conservation of energy, ensuring a conversion efficiency of 29.2% for wood fuels. Table 4 presents the results of the yield calculations and summarises the performance

[21] As the pollutant ratios are assumed to be identical for *Grevillea robusta* and Eucalyptus, and similar for Acacia, energy losses due to volatile PIC may only differ in marginal ranges (see below); therefore, in light of the principle of conservation of energy, an identical share of primary energy needs to be devoted to char.

indicators of the TLUD gasifier with different feedstocks. Maize cobs have a slightly higher energy yield of 29.5%, which partly compensates for their lower thermal efficiency. However, as laid out in the next paragraphs, maize cobs cause higher PIC emissions, which explains the remaining difference in overall energy recovered. The carbon content of maize cob char is determined based on the equation from Sheng and Azevedo (2005). The result compares well with the value reported by Torres (2011).

**Table 4.** Performance of the TLUD gasifier with different feedstocks

| Feedstock | *Grevillea robusta* | Eucalyptus | Acacia | Maize cobs |
|---|---|---|---|---|
| Conversion efficiency | 29.2% | 29.2% | 29.2% | 29.5% |
| Mass yield d.b. | 21.6% | 18.2% | 16.9% | 19.4% |
| C yield | 24.0% | 30.1% | 30.2% | 33.9% |
| C content d.b. | 75.6% | 75.6% | 75.6% | 82.8% |

**Stove emissions.** As explained in subsection 2.4.1, the TLUD gasifier separates gas generation and combustion in two distinct phases, thereby allowing for a higher fuel efficiency and lower PIC emissions than conventional stoves. Although several studies have shown that the performance varies with stove design (e.g., insulation, stove mass to heat, fan, chimney), fuel properties (e.g., unit size, bulk density, moisture content), or handling and process flow (e.g., high power for bringing to boil, low power for simmering, refilling the fuel container), pyrolytic or semi-gasifier stoves are currently the cleanest and most efficient option for small-scale cooking with solid biomass fuels (Huangfu et al., 2014; Jetter et al., 2012; Roth, 2014, pp. 36–42; Tryner et al., 2014). Currently, emission factors specific to char-producing cook stoves are only available for CO and PM (see Andreatta, 2007; Huangfu et al., 2014; Tryner et al., 2014). More comprehensive sets of pollutants from TLUD gasifiers were measured during laboratory experiments[22] by Jetter et al. (2012) and MacCarty, Ogle, Still, Bond, and Roden (2008). While the results of the former study definitely include the combustion of the char in the gasifier, it is not explicitly mentioned in the latter publication. Meanwhile, several assessments of biochar production have used the pollutant ratios of MacCarty et al. (2008), assuming that they would not include char combustion and averaging the values from high and low power operation (see Scholz et al., 2014; Sparrevik, Field, Martinsen, Breedveld, & Cornelissen, 2013; Whitman et al., 2011).

This thesis uses the molar emission ratios of MacCarty et al. (2008), measured for a household gasifier stove fuelled with wood sticks from Douglas fir. The ratios are converted into pollutant mass and scaled according to the carbon content of different wooden feedstocks (i.e., *Grevillea robusta* and Eucalyptus for on-farm wood, and Acacia for off-farm wood). For maize cobs, the ratios for CO and TSP are adjusted, since several studies suggest that maize cob fuel generally combusts less cleanly (see, e.g., Jetter et al., 2012), and that the need to reload the micro-gasifier due to the low bulk energy density of maize cobs leads to emission spikes in CO and eventually PM (Tryner et al., 2014). Data on indoor-air concentrations of CO and $PM_{2.5}$ during cooking tests with the TLUD gasifier from the Biochar Project confirm that tendency (Njenga et al., 2016). Compared to wood, the ratios of $CO/CO_2$ and $TSP/CO_2$ are increased by factors of 1.5 and 2, respectively. Subsequently, the emission factors are calculated following the same steps as described for wood.

According to the procedure of the Water Boiling Test, the cold start high power phase begins with the fuel catching fire, and ends abruptly as soon as the water reaches the local boiling temperature; for the low power phase, the water is kept close to three degrees below the boiling

[22] For details on the procedure and limitations of the Water Boiling Test, see Global Alliance for Clean Cookstoves (2014)

point in order to assess the stove's simmering performance (Global Alliance for Clean Cookstoves, 2014, pp. 13–19). The field measurements of the Biochar Project showed that the TLUD gasifier took 11 minutes to bring water to boil, irrespective of the fuel type (Njenga et al., 2016), whereas the total cooking time (excluding reloading if necessary) was around 30 minutes (Helander & Larsson, 2014, p. 21). In order to account for the longer simmering phase, the emission factors from high and low power operation are weighted accordingly. The weighted average is likely to model the emissions from actual cooking practices more precisely than one operation mode alone. However, note that this method omits that relative to its duration, the high power phase might consume a larger share of fuel carbon than the lower power phase. For a better estimate based on Water Boiling Test data, the fuel consumption during the first phase would need to be determined by weighing (VITA, 1985, pp. 26–28).

Data gaps for $N_2O$ emissions are filled with factors from conventional charcoal production from wood. For maize cobs, the value is scaled according to the feedstock's higher nitrogen content. The emission factors of sulphur dioxide result from the same procedure as in the reference system, assuming the 20% to 80% distribution between production and consumption of charcoal to be valid for all feedstocks.

### 4.3.1 Charcoal system: char to energy

In the charcoal system, the harvested char is used as a fuel for the Kenya Ceramic Jiko, thereby replacing conventional charcoal from the market (see Figure 18).

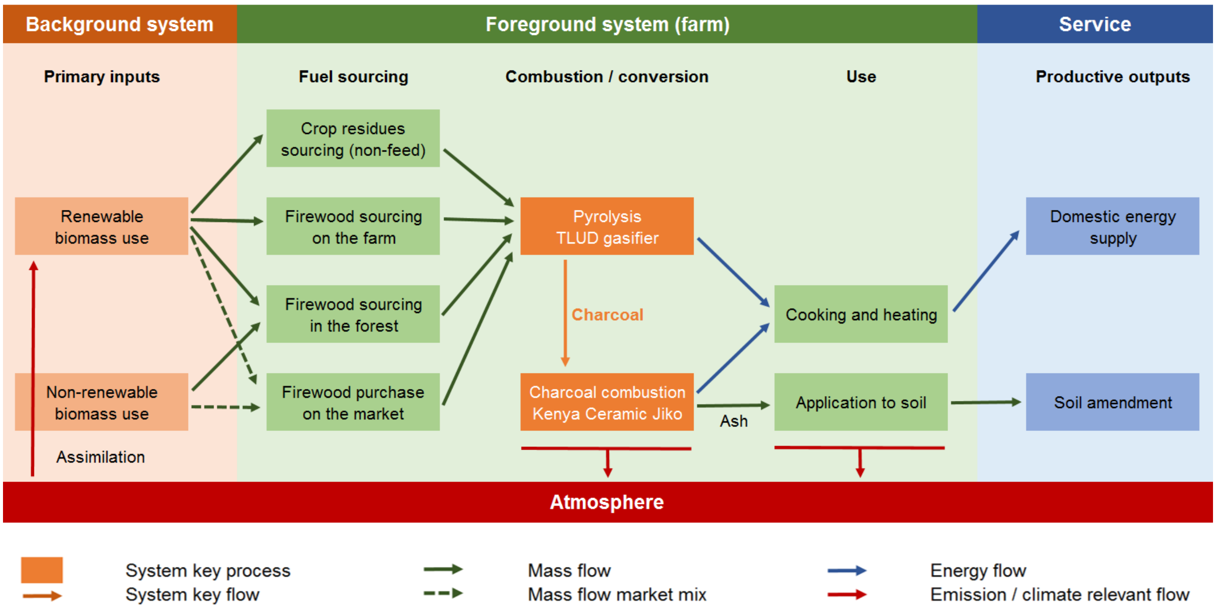


**Figure 18.** Charcoal system: improved cooking combined with charcoal production, subsequent use of charcoal as a fuel

**Stove emissions.** The use of TLUD char as a cooking fuel is modelled after the combustion of conventional charcoal in the KCJ as described for the reference system (see section 4.2). For different types of wood charcoal, all pollutant ratios are held constant. However, cooking tests for the Biochar Project showed that maize cob charcoal causes significantly higher indoor air concentrations of CO and $PM_{2.5}$ (see Achour, 2015, pp. 30–40). Similar to char production, the ratios of $CO/CO_2$ and $TSP/CO_2$ are increased by factors of 1.5 and 2, respectively, compared to combustion of wood charcoal.

**Thermal efficiency.** During the cooking tests with the KCJ, the energy delivered to the pot was not measured directly. Similar to the approach for the gasifier, the thermal efficiency of project specific stove-fuel combinations is determined in relation to burning conventional charcoal in the KCJ, using a well-established value of 30% efficiency as in the reference system (MoE, 2002, p. 56). According to the measurements from Achour (2015, p. 22), cooking a standard meal with the KCJ requires less fuel energy with charred *Grevillea robusta* or maize cobs than with conventional charcoal, leading to a thermal efficiency of 40% and 32%, respectively[23]. The good performance of *Grevillea robusta* charcoal mainly results from its lower energy density; since a low power level is sufficient for cooking a standard meal, energy-rich fuels supply excess energy if the stove is fully loaded, irrespective of the fuel type (Achour, 2015, pp. 25–48). Despite their similar energy density, charred maize cobs did not perform as well during the cooking tests. The light and porous material showed a high burning rate and consequently an increased power level, making the cooking process less efficient (Achour, 2015, pp. 47–48). Charred Eucalyptus and Acacia wood were not included in the field study. Therefore, they are assigned to the higher efficiency level of 40% and the low lower efficiency level of 30%, respectively, according to their energy content and the power level at which they are likely to operate.

**Fuel use and energy consumption.** Net energy consumption ($EC_{net}$) is calculated from the fuel consumption of each biomass type b ($FC_b$) and the corresponding mass-based conversion factor from raw material to char ($m_b$). This factor describes the gasifier's conversion efficiency and determines the proportion of feedstock available for combustion in the second stage. Moreover, the lower heating value of each raw and carbonised fraction of biomass type b ($LHV_b$ and $LHV_{bc}$, respectively) and the thermal efficiencies of the stove-fuel combinations ($\eta_{TLUD}$ with primary feedstocks and $\eta_{KCJ}$ with charcoal) are critical:

$$Charcoal\ EC_{net} = \sum_{b=1}^{n} \eta_{TLUD} * FC_b * LHV_b + \eta_{KCJ} * m_b * FC_b * LHV_{bc}$$

### 4.3.2 Biochar system: char to soil

In the biochar system, the harvested char is applied to agricultural soils, where it improves physical and chemical soil properties and sequesters carbon. However, this means that it does not contribute to energy supply. In the system's default version as shown in Figure 19, the off-heat from the carbonisation process is the only source of thermal energy for cooking. If modelling in the downstream perspective reveals that the net energy demand cannot be adequately met with the limited feedstocks available, charcoal purchase on the market and its combustion in the Kenya Ceramic Jiko need to be added to the system.

[23] The values reported here are not identical with previous project publications because Achour (2015, p. 47) did not account for variations in moisture content between different types of charcoal.

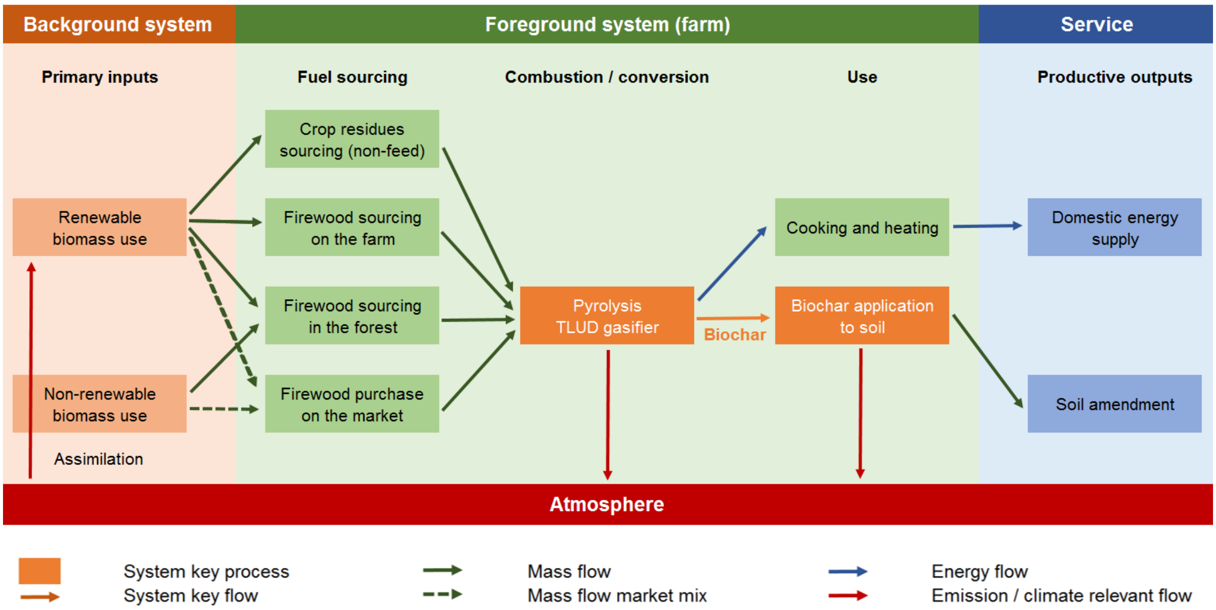


**Figure 19.** Biochar system: improved cooking combined with biochar production, subsequent use of biochar as a soil amendment

**Fuel use and energy consumption.** Net energy consumption ($EC_{net}$) is calculated from the fuel consumption of each biomass type b ($FC_b$), the corresponding lower heating value ($LHV_b$) and gasifier's thermal efficiency ($\eta_{TLUD}$) as

$$Biochar\ EC_{net} = \sum_{b=1}^{n} \eta_{TLUD} * FC_b * LHV_b$$

If the net energy demand cannot be adequately met by recovering off-heat from conversion in the TLUD gasifier, charcoal combustion in the Kenya Ceramic Jiko is added as follows:

$$Biochar\#2\ EC_{net} = \eta_{KCJ} * FC_c * LHV_c + \sum_{b=1}^{n} \eta_{TLUD} * FC_b * LHV_b$$

**Permanence of biochar.** The stability of biochar and its capacity to sequester carbon depend on three major factors that vary strongly by production technology and local conditions. First, the carbonisation process determines which share of the original feedstock's carbon content is conserved; second, the ratio of the recalcitrant to the labile fraction shapes the decomposition; and third, climate and soil conditions, microbial activity and abiotic factors such as erosion limit the potential mean residence time of more than one thousand years (Scholz et al., 2014, pp. 4–43). Only local data from a long-term field study would allow for an accurate assessment. As they are currently not available from the Biochar Project, 80% recalcitrant fraction and 500 years MRT are chosen as default values, following the recommendations by Whitman et al. (2010). The remaining labile fraction has an MRT of 15 years and is thus mineralised during the period assessed (Whitman et al., 2010). The model treats putting biochar to soil equally to stove-fuel combinations, with the labile carbon fraction being fully oxidised to $CO_2$.

# 5 System performance and climate impact

The following sections present the results from the two modelling approaches and the sensitivity analysis for selected parameters and choices. Due to the large number of possible combinations, not all results can be presented here. However, the Excel model using pivot tables and charts allows to analyse many variations without additional calculation steps. Whenever settings are fixed as a default to study the effect of varying a specific parameter, other options are also tested to ensure that they do not alter the tendency of the results. The three main levels of analysis are (a) the system level; (b) the level of stove-fuel combinations; and (c) the level of stove-stove combinations. To keep it simple, the model treats biodegradation of maize cobs and putting biochar to soil equally to stove-fuel combinations, with 0% thermal efficiency and labile carbon being entirely released as $CO_2$.

## 5.1 Downstream perspective: constant fuel input

In the first modelling approach, all unprocessed feedstocks available (i.e., on-farm and off-farm wood, maize cobs) are fed into each system, resulting in different quantities of net energy. As the reference system is not able to meet the annual net energy requirement from unprocessed feedstocks alone, conventional charcoal is added to cover the remaining energy need. Due to the higher thermal efficiency of the TLUD gasifier, neither the charcoal nor the biochar system need conventional charcoal.

**The system level.** The yellow bars in Figure 20 illustrate the constant supply of 78 GJ gross energy from unprocessed feedstocks to the improved systems. The supply to the reference system is increased by 29 GJ, which covers the energy content of conventional charcoal and conversion losses. The other bars show the differences in yield of net energy and biochar, and the resulting climate impact of each system.

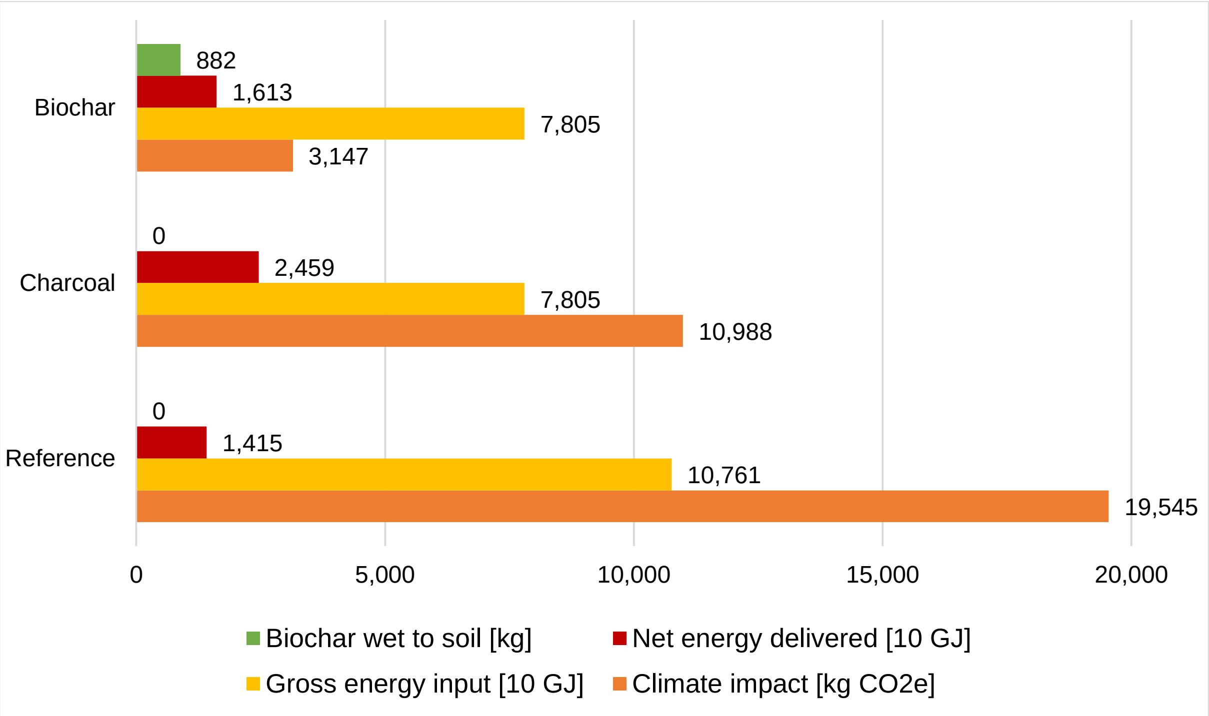


**Figure 20.** Downstream model at system level: climate impact and services from consuming all feedstocks available per household and year in each system, plus conventional charcoal in baseline; GWC is calculated using set 2 and $GWP_{20}$

The GWC as presented above is calculated using the large set of climate forcing agents (emission set 2) and $GWP_{20}$ characterisation factors as a default. This raises the question of how the results change due to using different pollutant sets and time frames. As Figure 21a shows for each system, set 2 finds a higher climate impact than set 1, irrespective of the time frame, and $GWP_{20}$ finds a higher climate impact than $GWP_{100}$, irrespective of the pollutant set. Interestingly, the biochar system has a negative GWC with any combination of pollutant sets and time frames, apart from set 2 and $GWP_{20}$, which comparatively weighs the credit from carbon sequestration the lowest. For policy recommendations, it is less important how the performance of each system changes in absolute terms, but rather how the relationships between the systems are affected. As Figure 21b indicates, switching towards set 2 and $GWP_{20}$ strongly reduces the GWC saving potential of the biochar system from 150% to 84%. On the contrary, the charcoal system is less affected than the baseline, leading to a slight gain in savings from 37% to 44%. While in absolute terms, the results are sensitive to such changes in the assessment framework, the ranking of alternatives remains robust. Even under the least favourable settings for the biochar system, which at the same time benefit the charcoal system, the biochar system performs best.

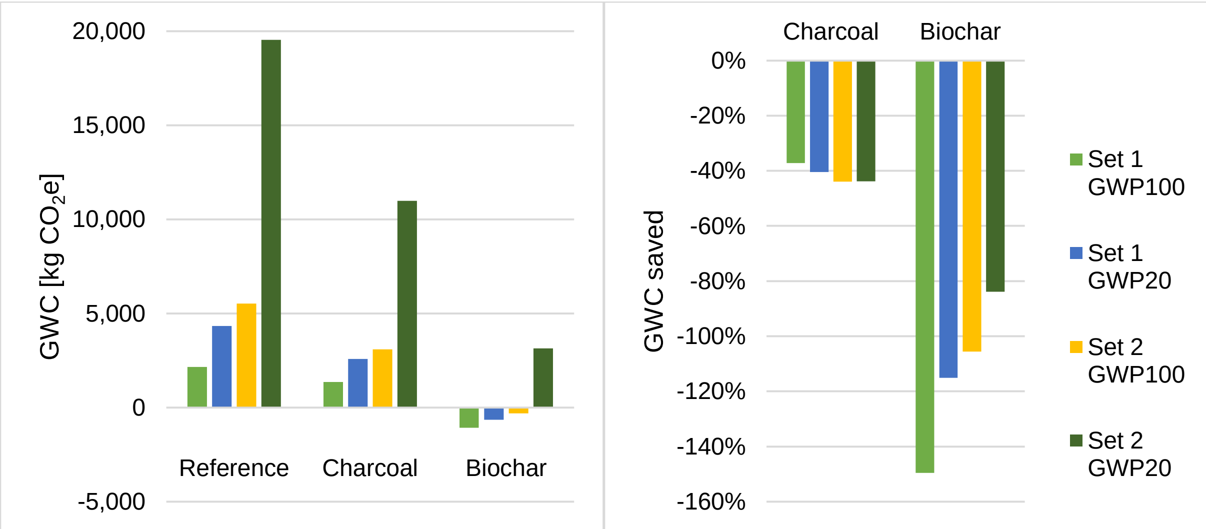


**Figure 21.** Impact of using different pollutant sets and time frames: (a) on the absolute climate impact of each system in kg $CO_2e$; (b) on the climate change mitigation potential in relation to the reference system in % GWC saved

Recalling energy supply for cooking as the main function, it appears distorting to compare the systems despite varying energy outputs. Therefore, the same figures are calculated per GJ of net energy delivered to the pot. As Figure 22 shows, this improves the relative performance of the charcoal system, which has the highest overall thermal efficiency. Nevertheless, the savings of 64-68% still lag behind those of the biochar system, which range from 86% to 144%.

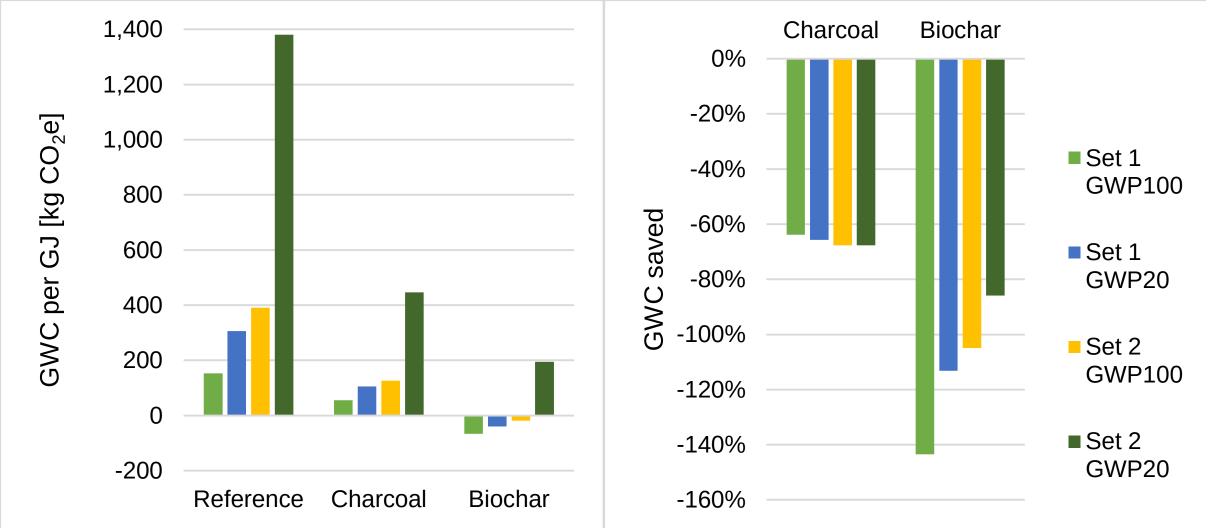


**Figure 22.** Impact of using different pollutant sets and time frames: (a) on the relative climate impact of each system in kg $CO_2$e per GJ net energy; (b) on the climate change mitigation potential per GJ net energy in relation to the reference system in % GWC saved

The next level of analysis breaks the systems further down into stove-fuel combinations, revealing the major sources of each system's climate impact. In order to account for differences in thermal efficiency, the results are expressed per GJ net energy delivered to the cooking vessel. Depending on the research interest, this comparison may aim at analysing stove-fuel combinations (a) individually, or (b) in their context of use.

**Stove-fuel combinations.** The former option looks at each energy providing process in isolation to evaluate its climate impact. This technology-centred approach works well to assess independent single stage processes (e.g., firewood combustion in the three-stone stove), or to compare alternatives on the same stage while holding preceding or succeeding processes constant. If this is not the case (e.g., charcoal production as the first stage, and combustion as the second stage), the interpretation should carefully consider that in practice, none of the parts of the process chain can stand alone. Figure 23 summarizes the results, showing that the TLUD gasifier is the cleanest alternative to provide 1 GJ of cooking energy. This is insofar surprising, as the gasifier's thermal efficiency is considerably lowered by leaving behind energy-rich char instead of combusting the feedstock entirely. Despite the Kenya Ceramic Jiko being more efficient and using what is perceived as a better quality fuel, it more than doubles the GWC of the gasifier. The comparatively poor performance of any char type in the KCJ gives rise to doubt that from a climate perspective, charcoal should be promoted as a cleaner fuel, given the current stove technology which is yet considered as "improved".

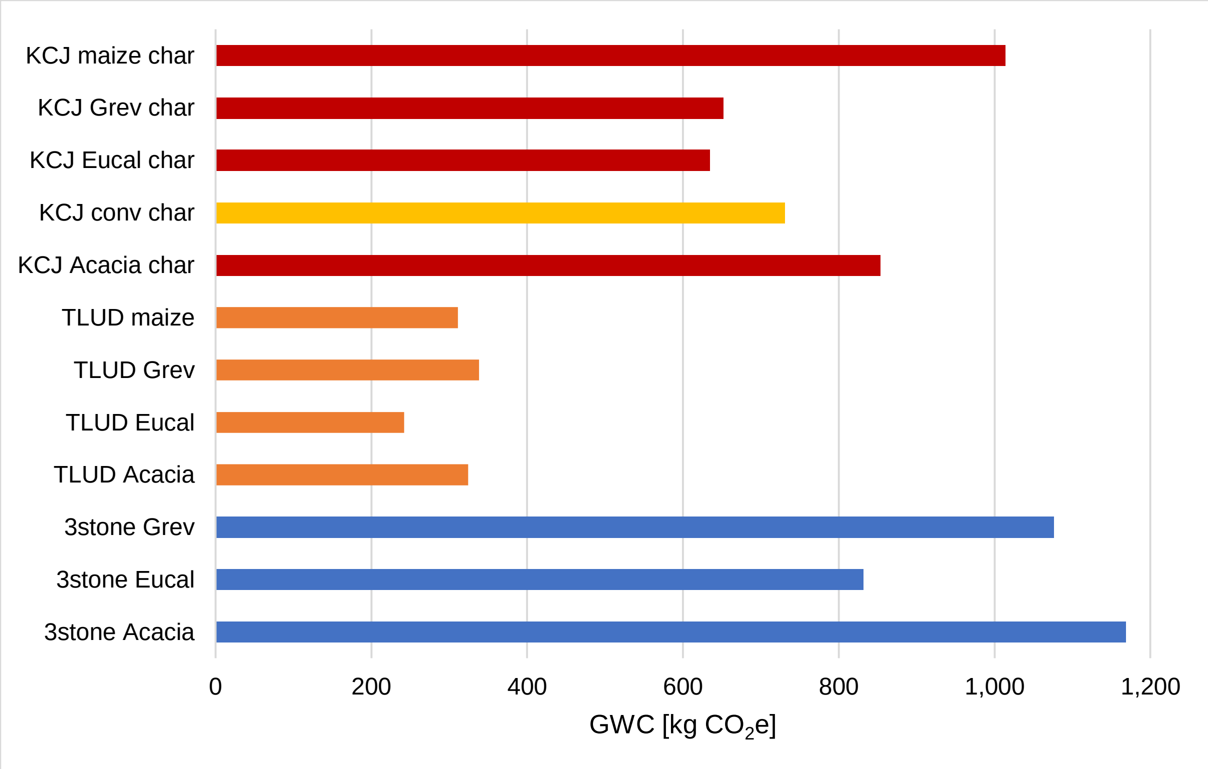


**Figure 23.** Downstream model at stove-fuel level: comparison of the climate impact if single stove-fuel combinations are to deliver 1 GJ net energy to the pot; GWC in kg $CO_2$e is calculated using set 2 and $GWP_{20}$

However, the notion of charcoal being a better fuel comes less from a climate perspective than from concerns about health, combustion efficiency and comfortable handling. Breaking down the results by pollutant species reveals that supplying 1 GJ of net energy from charcoal in the KCJ instead of wood from the traditional three-stone stove increases CO emissions, but clearly reduces particulate matter. Since high concentrations of carbon monoxide and particles inside of unvented dwellings are the major health risks related to cooking, it becomes plausible why charcoal is preferred over traditional wood stoves; not only from a single-process perspective, where the charcoal stove benefits from a twofold thermal efficiency, but also if the whole process chain is considered. Since traditional conversion in earth mound kilns takes place outside, it diverts pollution from kitchens to ambient air where it is a negligible issue for health. With Eucalyptus wood serving as an example, Figure 24 compares stove-fuel combinations that draw on the same primary feedstock in terms of emissions on a pollutant mass basis in relation to the three-stone stove. The fact that the gasifier has a higher thermal efficiency than the three-stone stove and converts around 30% of the feedstock's carbon content to char explains why its emission levels are lower for any pollutant. Stronger reductions in most PIC than in $CO_2$ reflect the cleaner combustion process.

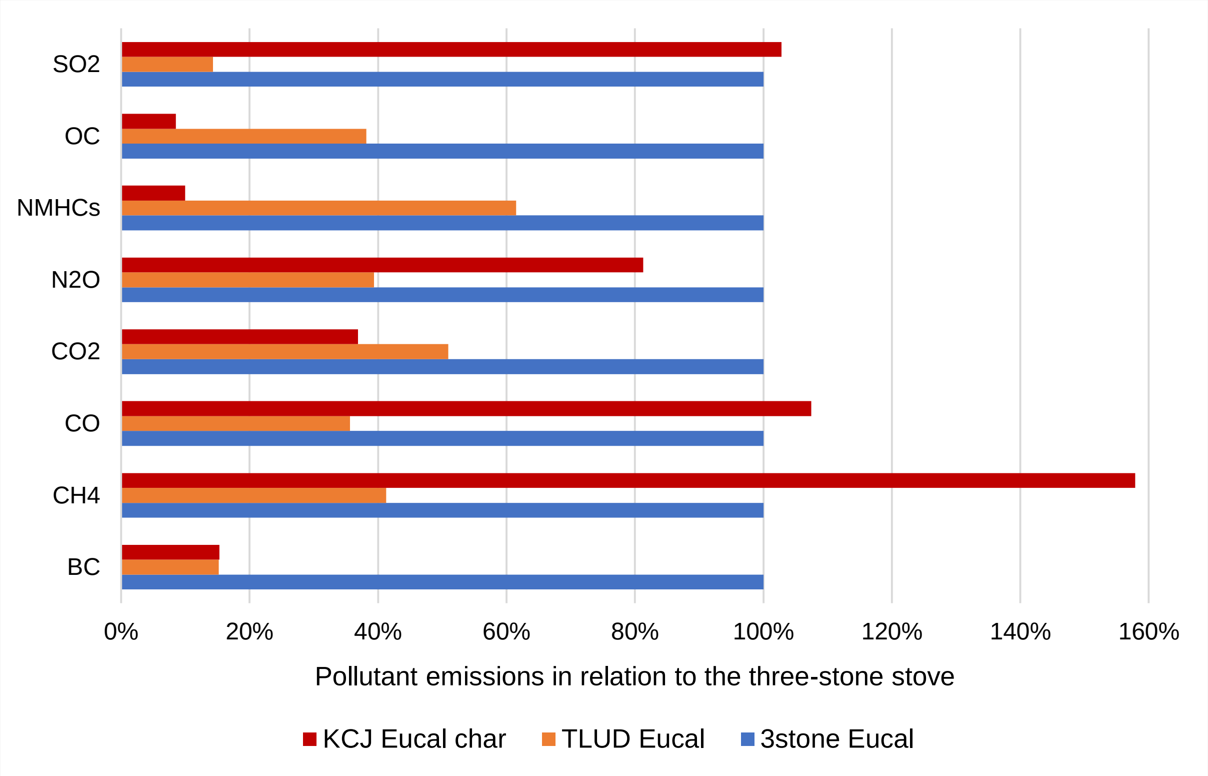


**Figure 24.** Downstream model at stove-fuel level: emissions on a pollutant mass basis in relation to the three-stone fire if different stoves use Eucalyptus as a primary feedstock to deliver 1 GJ net energy to the pot; emissions from converting wood to charcoal are not included

Translated into the climate impact of different pollutant species, Figure 25 makes a similar comparison in terms of GWC (though not in relation to the three-stone stove) and gross energy input needed to supply 1 GJ net energy. For charcoal, the number in brackets additionally accounts for losses during conventional conversion. The results show that from a climate perspective, the critical pollutants are methane and CO for char combustion, and black carbon and CO for the three-stone stove, respectively. In comparison to the gasifier, both stoves convert a considerable share of fuel carbon into products of incomplete combustion (see also Figure 24). This indicates room to improve thermal efficiency, which would lower the fuel consumption and thus again cut down the emissions in relation to net energy consumption. While this is apparent for the three-stone stove, "improved charcoal stoves" such as the KCJ are usually less associated with incomplete combustion. The credit for renewable biomass (RB-credit) accounts for $CO_2$ uptake during feedstock regrowth.

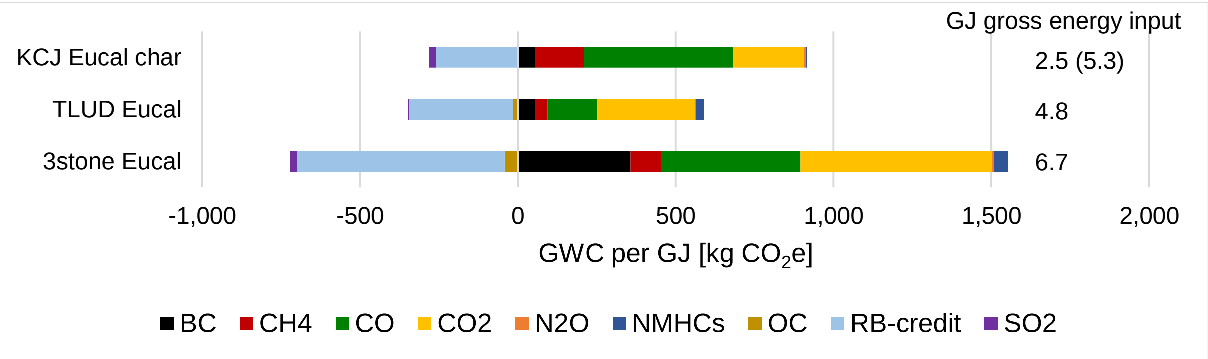


**Figure 25.** Downstream model at stove-fuel level: comparison of gross energy input and GWC by pollutant species if different stoves use Eucalyptus as a primary feedstock to deliver 1 GJ net energy; GWC in kg $CO_2e$ is calculated using set 2 and $GWP_{20}$; converting wood to charcoal is not included

**Stove-stove combinations.** The second option to analyse stove-fuel combinations in their context of use locks single operations in process chains as determined by the system description (see chapter 4). Using the example of the charcoal system, this means that any feedstock converted by the gasifier needs to be supplied to the KCJ; vice-versa, the KCJ has to use no more or less charcoal than delivered by the gasifier. This construction allows to assess process chains on a common basis, i.e., in relation to gross energy entering the first stage, or in relation to the sum of net energy delivered. While the results do not allow to compare individual stove-fuel combinations across different process chains (as done in the previous charts), they provide the basis to evaluate alternative use patterns at an aggregate level, or to identify GWC hot spots within a process chain. The farm model names these process chains "stove-stove combinations" because none of them involves more than two-stages or stove types:

- Conventional charcoal: earth mound kiln (EM) + Kenya Ceramic Jiko (KCJ)
- Eucalyptus charcoal: TLUD gasifier (TLUD) + Kenya Ceramic Jiko (KCJ)
- Eucalyptus biochar: TLUD gasifier (TLUD) + biochar to soil (Biochar)

Net energy is calculated as the sum of energy delivered to the cooking pot by different stages of the process chain, e.g., char production in the gasifier, and char combustion the KCJ. In contrast to the single-process perspective, the second analysis includes processes that do not directly deliver cooking energy but are part of an energy-supplying process chain, i.e., wood conversion in the earth mound kiln or biochar to soil. As it is not linked to any energy service, the biodegradation of maize cobs is omitted.

Figure 26 compares the climate impact of different stove-stove combinations delivering 1 GJ net energy to the cooking pot and contrasts it with gross energy consumption. The comparison shows that conventional charcoal has by far the highest climate impact, followed by the three-stone fire using different types of wood. At the same time, the process chains in the reference system need double the fuel energy input of the charcoal system. This is due to the considerably lower overall thermal efficiency as given next to the red bars. For conventional charcoal, the losses during conversion completely offset the higher efficiency of the KCJ compared to the three-stone fire. From all stove-stove combinations, those in the charcoal system reach the highest overall efficiency with up to 33%. Despite the increased feedstock consumption compared to the charcoal system, the process chains in the biochar system have the lowest climate impact. This is not only thanks to carbon sequestration, but also because of the better performance of the gasifier than the KCJ in delivering an equal amount of net energy (see individual comparison in Figure 23).

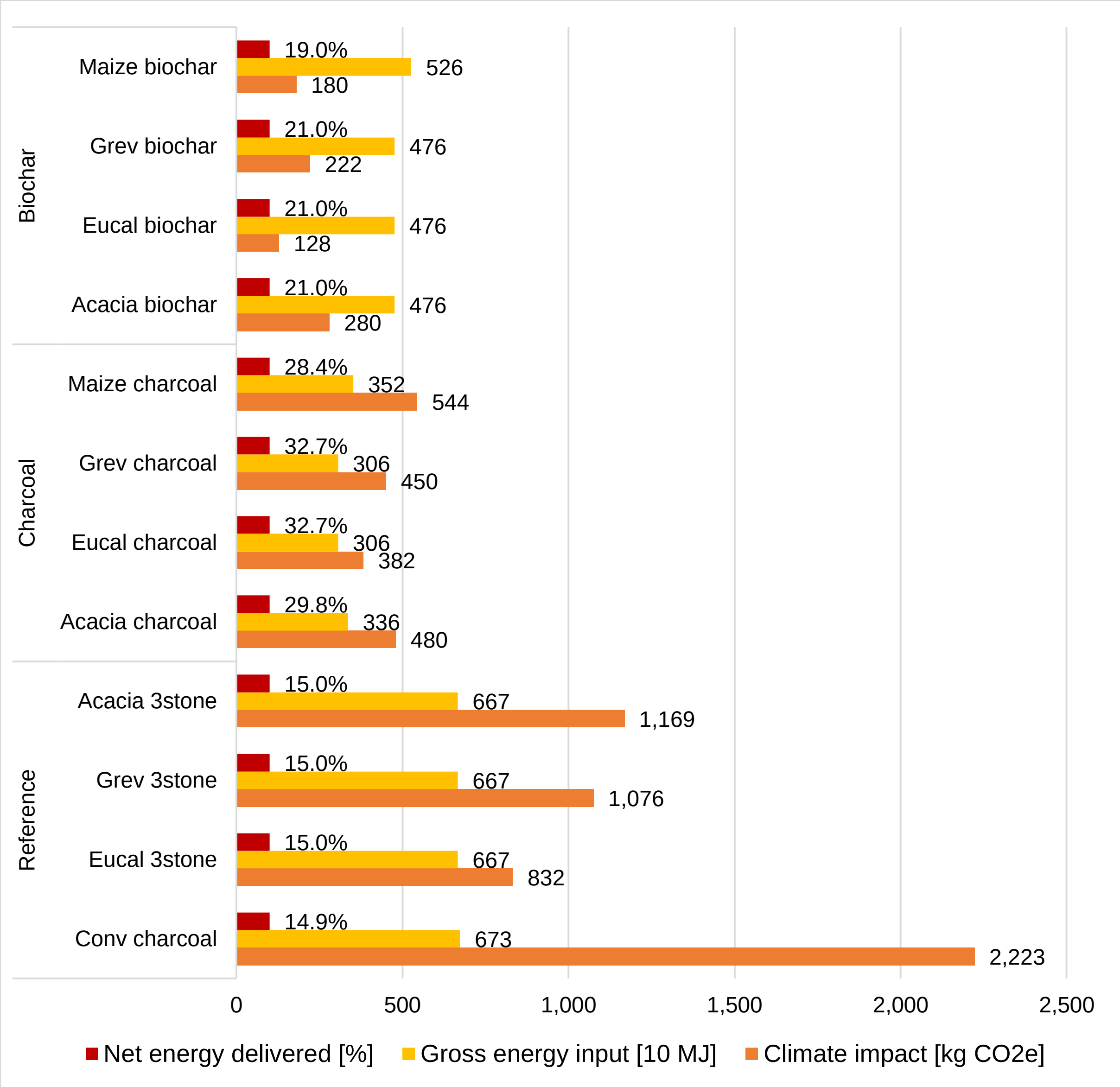


**Figure 26.** Downstream model at stove-stove level: gross energy consumption [10 MJ] and climate impact from different process chains delivering 1 GJ net energy to the pot; GWC in kg $CO_2e$ is calculated using set 2 and $GWP_{20}$; the net energy yield is illustrated in 10 MJ and labelled as % of gross energy

In order to identify emission hot spots within systems or process chains, Figure 27 divides the climate impact of each stove-stove combination into contributions from single stages. The considerable differences between similar combinations (e.g., KCJ with conventional or TLUD char) reflect the strong leverage effect of thermal efficiency. This also explains why on a net energy basis the gasifier performs better in the charcoal than in the biochar system. The breakdown shows a changing relationship between conversion and combustion in charcoal process chains: On the one hand, conversion in the earth mound kiln clearly dominates the climate impact of traditional practices; this highlights the importance of a life cycle oriented evaluation that does not only look at the consumption stage, but equally accounts for background processes. On the other hand, conversion constitutes a minor share of GWC from the charcoal system's stove-stove combinations; although the gasifier delivers roughly two thirds of net energy (see Figure 28), char combustion causes the larger proportion of the climate impact. The reasons can be better understood when stove-fuel combinations are compared individually, as previously addressed by Figure 23 to Figure 25.

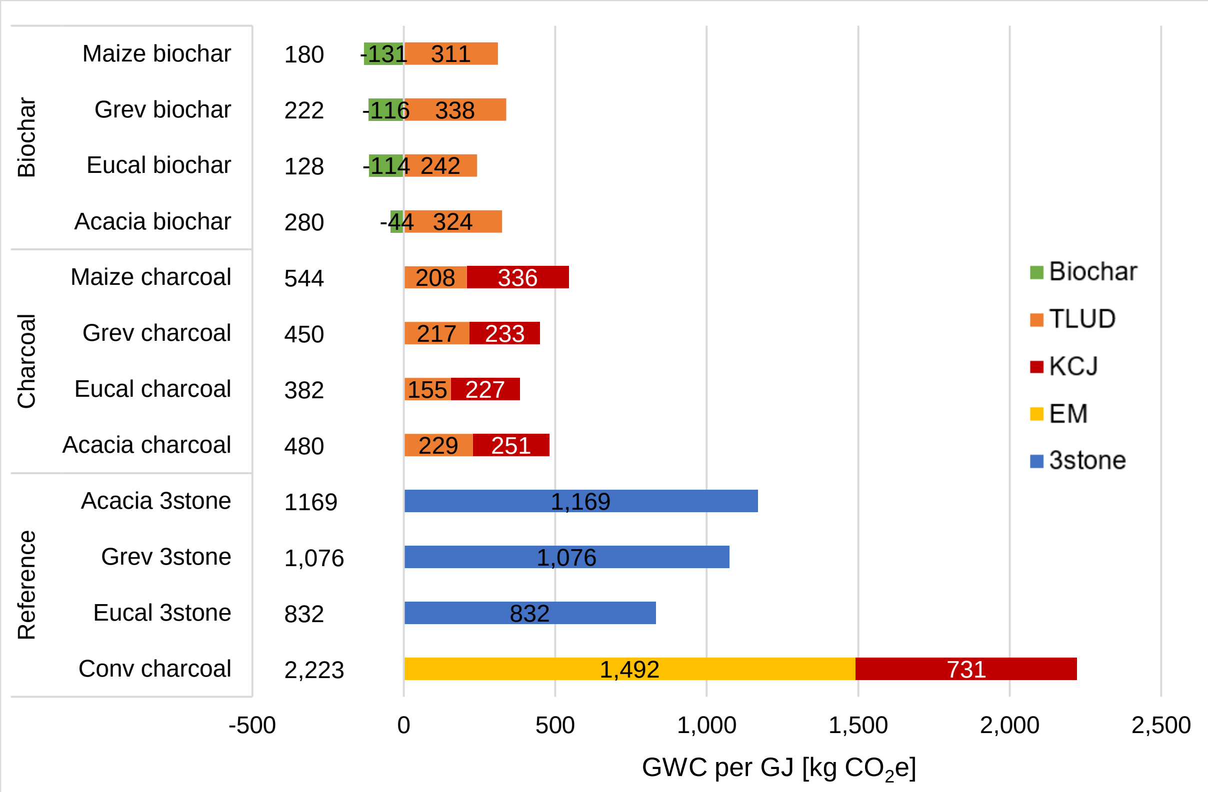


**Figure 27.** Downstream model at stove-stove level: comparison of the climate impact if different process chains are to deliver 1 GJ net energy to the pot; GWC in kg $CO_2$e is calculated using set 2 and $GWP_{20}$; the numbers in the column indicate the balance of GWC per process chain, whereas the bars break it down into contributions from single stages

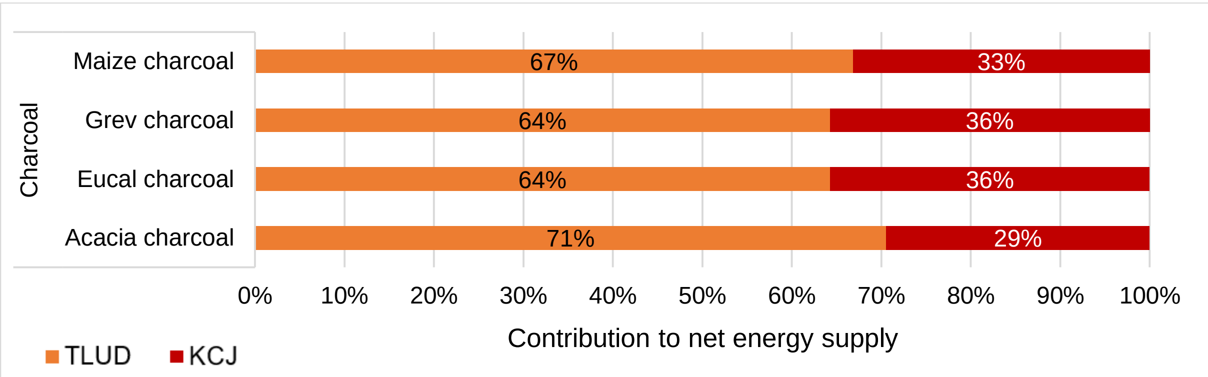


**Figure 28.** Downstream model at stove-stove level: contribution of single stages to net energy supplied by the process chain; in all other process chains, 100% of net energy is delivered by one stage alone (i.e., the KCJ in the case of conventional charcoal, or the TLUD gasifier in the case of biochar)

At the level of stove-stove combinations, looking into contributions of pollutant species to GWC becomes interesting again, because it also accounts for non-energy delivering stages. The breakdown helps to understand why the process chains do not perform equally well, and which pollutant species are critical for specific combinations. Using set 2 and $GWP_{20}$, products of incomplete combustion dominate the balance, with black carbon particles, carbon monoxide and methane as the main climate forcing substances (see Figure 29). This is more pronounced in the reference system, and strongest for conventional charcoal. In process chains of the improved systems, $CO_2$ causes an almost as large share of GWC as PIC. Combinations using maize cobs are an exception because they emit greater proportions of particulate matter and CO. Since $GWP_{100}$ puts a higher weight on long-lived climate forcing agents, $CO_2$ causes the main share of GWC for all process chains but conventional charcoal, where PIC are still dominant.

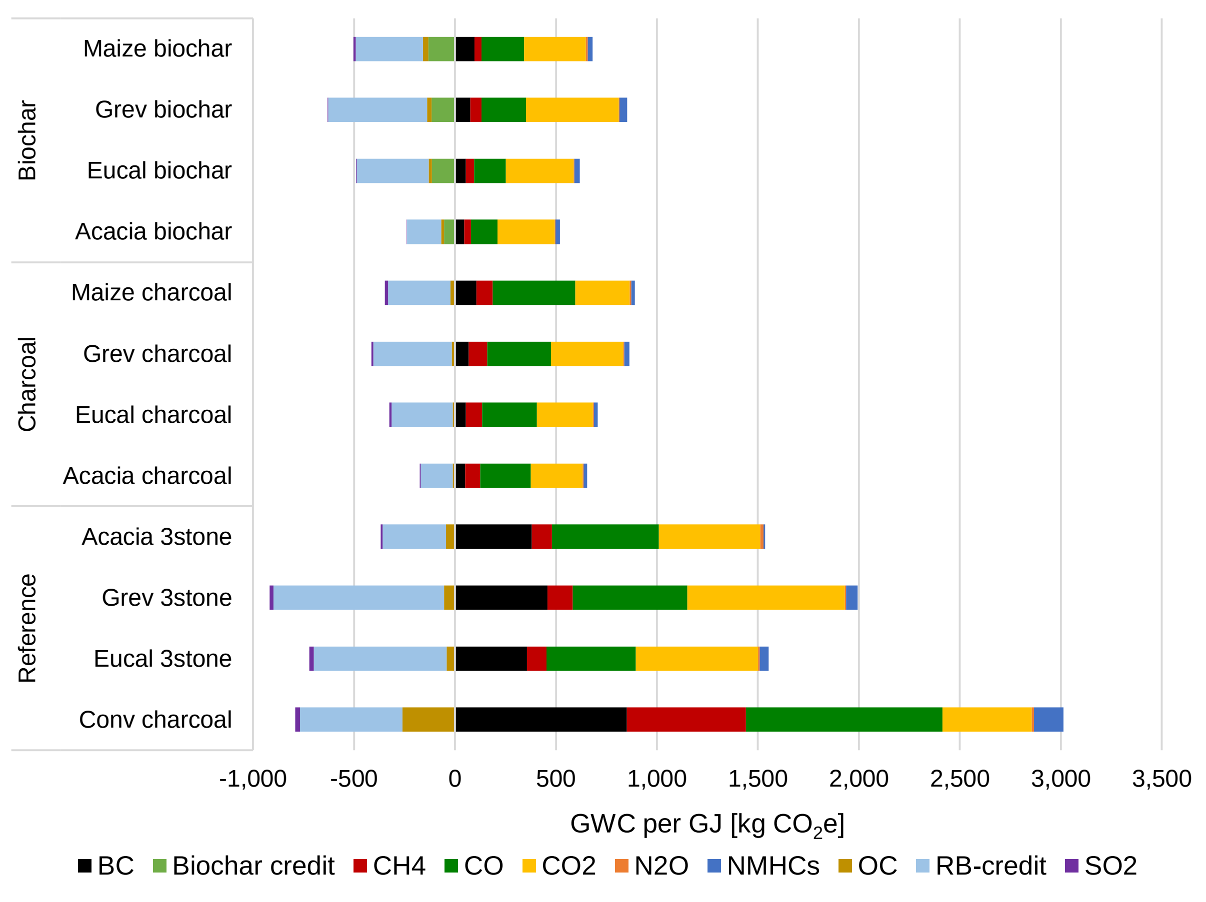


**Figure 29.** Downstream model at stove-stove level: comparison of different combinations' climate impact from delivering 1 GJ net energy to the pot; GWC is calculated using set 2 and $GWP_{20}$

For a pollutant-based evaluation of different primary feedstocks, the emission factors are not robust enough. Due to a lack of data for specific wood or charcoal types, most values are obtained from scaling factors according to carbon content, apart from Eucalyptus and Acacia used in the three-stone stove. Therefore, the variation results mainly from differences in carbon content and thermal efficiency, which is an uncertain parameter (see section 6.3 for a discussion on this constraint). In the case of Acacia, partly unsustainable sourcing lowers both the credits for renewable biomass combustion and biochar. Compared to woody biomass, the emission factors from using maize cobs reflect the increased levels of CO and PM emissions.

## 5.2 Upstream perspective: constant net energy supply

In the downstream model, both improved systems deliver more net energy than actually needed. For a comparison of performance based on an equal amount of net energy as in Figure 22, each system's climate impact is scaled down in relation to its average GWC. While the "all feedstocks in" assumption is an important basis for further analysis because it reveals strengths and weaknesses of stove-fuel combinations and process chains, it provides a poor framework for evaluating alternatives at the system level. In a situation of constrained resources, it is more likely that no more feedstocks than needed are used to meet energy requirements for cooking. Therefore, the second modelling approach optimises the systems to supply just as much net energy as needed at the minimal climate impact. Differences between the upstream and the downstream model only take effect on the system level.

The reference system remains unchanged and delivers the benchmark for net energy to be supplied by each system. In the improved systems, the most polluting feedstocks according to the stove-stove analysis are reduced first, using Excel's goal seek function for the fine tuning. Depending on pollutant set and GWP time frame, using Acacia wood or maize cobs has the highest GWC per GJ net energy in the charcoal system. Both can be reduced to zero without falling short of cooking energy. Irrespective of pollutants and GWP, *Grevillea robusta* is the third most polluting feedstock. Setting its input to 67% of the potentially available amount is sufficient to meet the net energy requirement of 1,415 GJ per year for the model household. In the biochar system, Acacia wood performs worst. It is the only feedstock that has a positive net GWC (i.e., the balance of GWC from conversion and the biochar credit) with set 1 and any GWP, and set 2 and $GWP_{100}$. Under set 2 and $GWP_{20}$, all feedstocks have a positive GWC, with Acacia having the highest. To stay above the net energy limit, Acacia can be reduced to 25% in the biochar system.

The comparatively poor results for Acacia do not result from its properties as a fuel, but from the 43% share of non-renewable biomass in off-farm wood. Reducing the input of Acacia is based on the assumption that this does not lower its fraction of NRB, which is a county wide average for Embu and thus independent of small extractions. In contrast, a consequential LCA would account for such changes in properties of marginal supplies.

Figure 30 presents the results of the upstream model, which further reduces the climate impact of the improved systems in relation to the baseline. Compared to the downstream model, particularly the charcoal system benefits from the optimisation because lowering the feedstock consumption leads to a proportional decrease in the climate impact. In the biochar system, the credit from carbon sequestration partly offsets the detrimental effect of fuel consumption. Consequently, the biochar system gains less from a reduction in feedstock input. Figure 31 compares differences in relative performance between the downstream and the upstream model, showing the gains from optimised fuel supply. The picture slightly varies with the pollutant set and time frame chosen, but the tendency remains the same.

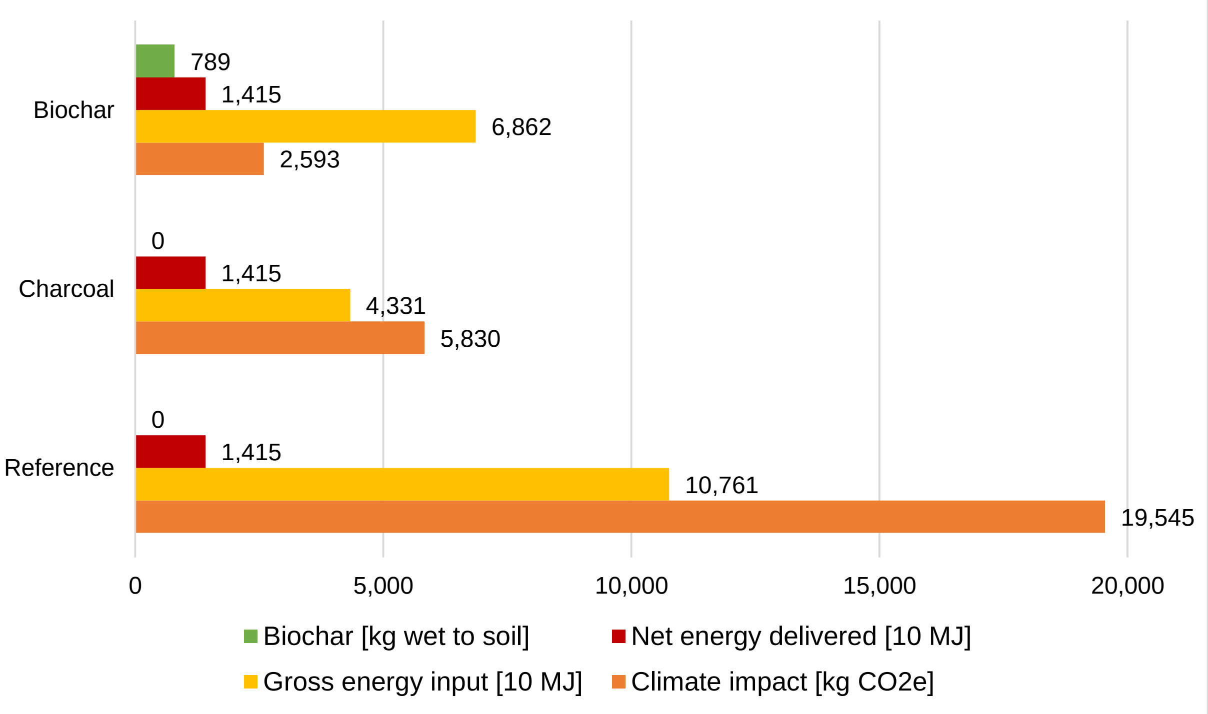


**Figure 30.** Upstream model at system level: climate impact, gross fuel energy consumption and biochar from each system delivering the minimal net energy required per household and year; the charcoal and the biochar system's feedstock consumption is optimised regarding GWC; GWC is calculated using set 2 and $GWP_{20}$

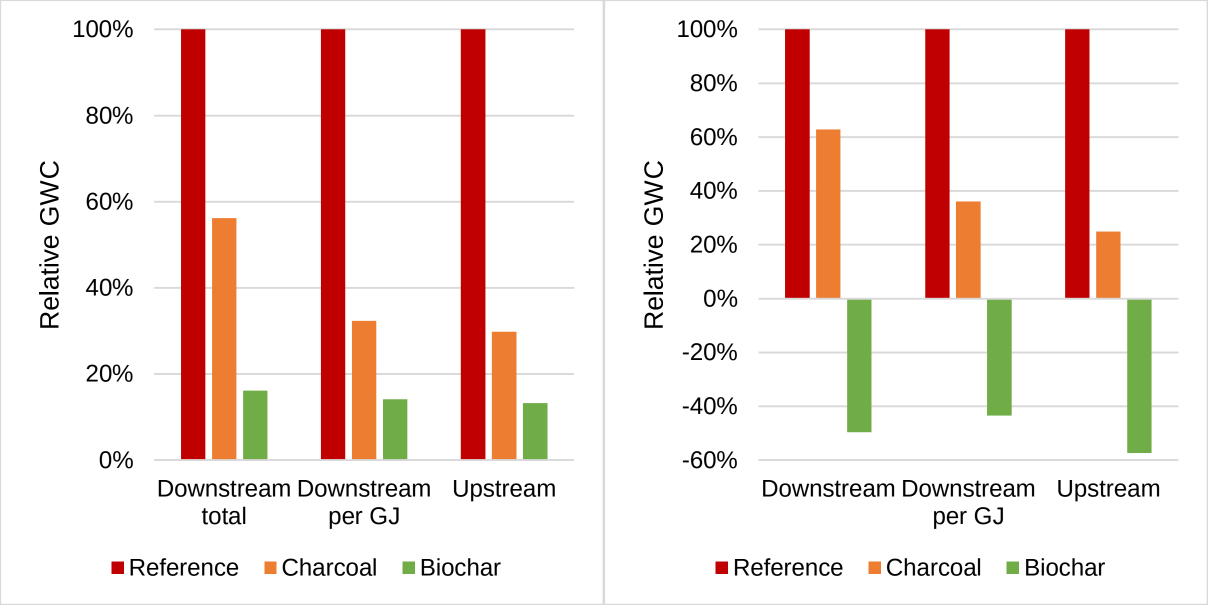


**Figure 31.** Performance of the improved systems in relation to the baseline, using the downstream and the upstream modelling approaches: (a) relative climate impact with set 2 and $GWP_{20}$; (b) relative climate impact with set 1 and $GWP_{100}$

In the upstream model, the charcoal and the biochar system cause 32% and 14% of the baseline's climate impact, respectively, using the large pollutant set and $GWP_{20}$. With Kyoto gases only and a time horizon of 100 years, the charcoal system's impact goes down to 25% of the baseline. The relative performance of the biochar system at -57% means that it does not only save 100% of the baselines impact, but additionally yields a net carbon credit.

## 5.3 Sensitivity analysis

Most steps of sensitivity analysis have already been included throughout this chapter. Since the fraction of non-renewable biomass is widely discussed as one of the key parameters in assessing bioenergy systems (Whitman et al., 2010), it is addressed separately in this section. The tests are computed in the downstream perspective to ensure that all feedstocks are represented in each system. As the effects showed to be similar with all pollutant sets and time frames, the following results are presented using set 2 and $GWP_{20}$. Starting from the initial default settings, the share of NRB is increased gradually in three steps:

1. Acacia at 43.3% NRB, all other feedstocks at 0% NRB (default)
2. Acacia at 100% NRB, all other feedstocks at 0% NRB
3. Any wood fuel at 100% NRB, maize cobs at 0% NRB
4. All feedstocks at 100% NRB

In the calculation scheme of pollutant set 2, increasing the fraction of non-renewable biomass has two effects: First, it cuts down the renewable biomass credit for carbon emitted; and second, it reduces the biochar credit for carbon sequestered in the biochar system. This explains why in absolute terms, the rise in GWC with increasing NRB is identical for the charcoal and the biochar system, which consume the same types and amounts of feedstocks. In any setting, the sum of the two credit types of the biochar system is exactly as high as the RB credit of the charcoal system. Increasing NRB always impacts slightly stronger on the reference system, because it additionally uses charcoal and has thus a higher carbon credit to lose. Figure 32a displays the potential rise is absolute GWC per system. In relative terms, however, the effect is largest for the biochar system, which starts from the lowest GWC under default settings, and smallest for the baseline (see Figure 32c). Consequently, the stepwise increase in NRB gradually reduces the comparative advantages of the improved systems. Nevertheless, the ranking remains robust: even under the assumption that 100% of all feedstocks are non-renewable, the charcoal system lowers the GWC by 36%, and the biochar system by 63% compared to the baseline. Figure 32b illustrates the relationship between systems' climate impact under different settings.

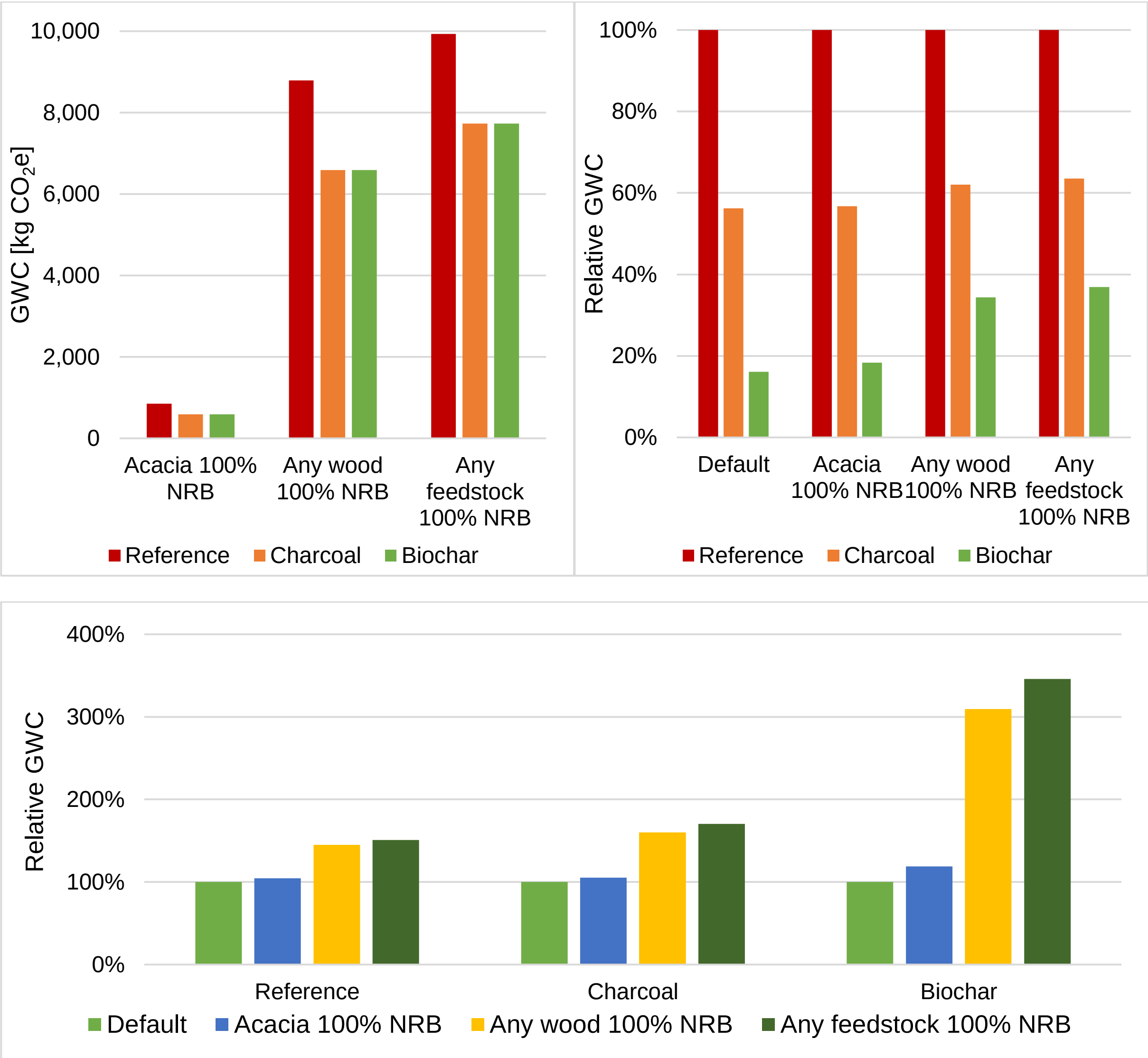


**Figure 32.** Impact of different NRB settings on the systems' performance: (a) increase in each system's absolute GWC in kg $CO_2$e; (b) systems' relative performance in relation to the reference; (c) each system's performance relative to the default settings; GWC is calculated using set 2 and $GWP_{20}$

Due to the less accurate calculation scheme of pollutant set 1, where only carbon emitted as $CO_2$ or $CH_4$ is taken into account, the carbon credits are slightly higher in the biochar than in the charcoal system. This is because biochar is assumed to release no other pollutants than $CO_2$, which is not the case for char combustions. However, the differences are minor and do not change the conclusions drawn from the sensitivity analysis.

Repeating the sensitivity analysis in the upstream model reveals that in a situation of 100% NRB, the charcoal systems climate impact may turn out lower than the biochar system's GWC, depending on pollutant set and time horizon. With set 1 and $GWP_{100}$, the GWC is 13% lower for the charcoal system. The reasons and implications of this finding will be further discussed in subsection 6.1.3.

# 6 Discussion

The results demonstrate that improved biofuel management simultaneously contributes to energy security, health protection and climate change mitigation. Irrespective of the modelling approach and even under the least favourable parameter settings, the charcoal and the biochar system show clear advantages over the traditional practices. While there are some trade-offs between those two strategies of improved resource use, the results leave no doubt about the gains from replacing open combustion and conventional charcoal by char-producing cook stoves. The following sections contrast the benefits and drawbacks of each system, reflect on their merit in practice and discuss central parameter and limitations to the research findings.

## 6.1 Interpretation and implications of the results

As laid out in the background chapter, organic resources play a key role for smallholder farmers' livelihoods and are related to multiple aspects of sustainable development (see Figure 33). While this interconnection offers the opportunity to use synergies and address various challenges at the same time (e.g., energy security, health and agricultural productivity), it also brings along the risk of undesirable side-effects. The initial idea behind this assessment was to compare the climate impact of different strategies to supply cooking energy and use available resources. For smallholder farmers, however, there is more at stake than net energy supply as the common function of the three systems, and their effects on climate change as the impact category in LCA. Most notably, the alternatives vary in feedstock consumption and biochar production, and thereby in their implications for health, time consumption, the household budget and soil quality. Although the system boundaries allow to exclude these side effects from LCA, they might be decisive for the implementation of a system in practice.

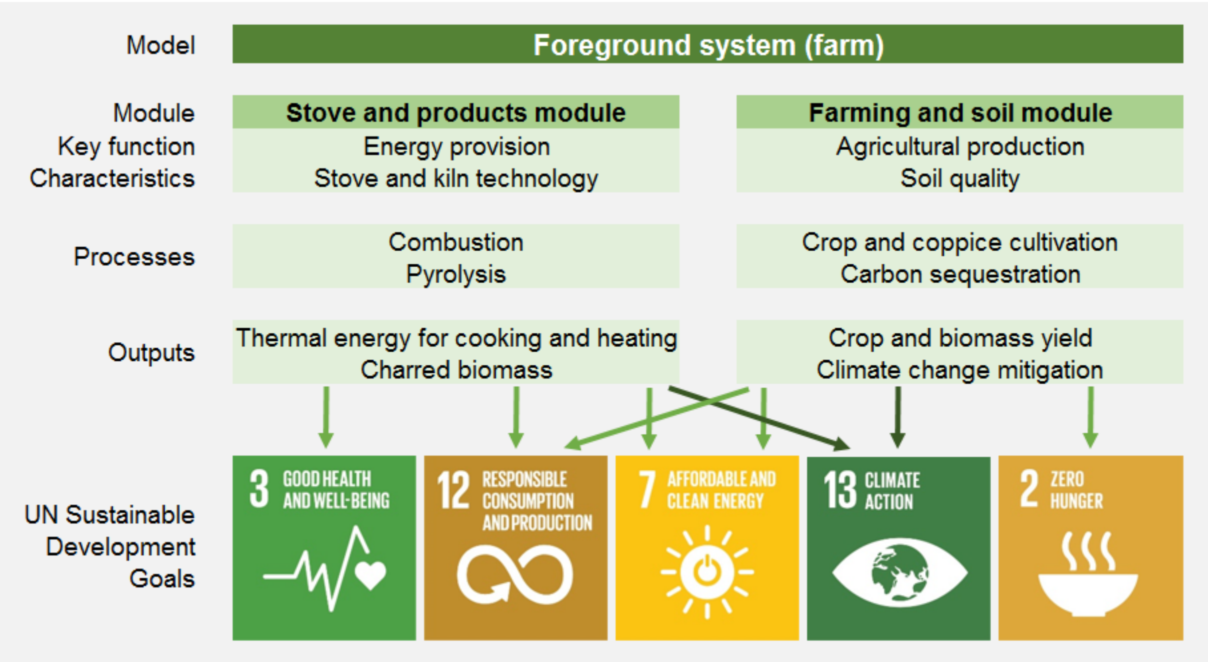


**Figure 33.** Links between the case study as implemented in the model, and UN goals for sustainable development (see Appendix F for the full figure)

For these reasons, the model does not only account for net energy in terms of services, but includes biochar as a non-mandatory co-product. Besides climate change as the main impact category, it calculates gross energy consumption and pollutant mass emissions, and allows to optimise the input of different feedstocks. Since modelling each of these factors towards comparable mid-point or end-point indicators in LCA lies beyond the scope of this thesis, they mainly serve as inputs to the discussion in this chapter, which addresses the following issues:

- full feedstock consumption (downstream perspective): average climate impact and net energy supply;
- minimum net energy supply (upstream perspective): optimised climate impact and feedstock consumption;
- yield of biochar for soil amendment: productivity and avoided emissions;
- gross energy input: time consumption, physical burden and monetary expenses; and
- pollutant emissions: indoor air pollution and health.

### 6.1.1 Stove performance and feedstocks

**Thermal efficiency.** If each system consumes all potentially available feedstocks (plus conventional charcoal in the baseline), the traditional practices supply the lowest amount of cooking energy, while having the highest climate impact. The fact that both improved systems deliver more energy at a lower GWC reflects the twofold importance of thermal efficiency. First, complete combustion and effective heat transfer maximise the share of fuel energy reaching the cooking vessel; and second, complete combustion converts fuel carbon primarily to $CO_2$, which has a lower Global Warming Potential that most individual PIC species, and causes a lower Global Warming Commitment than PIC in their sum.

In the upstream model, a third factor comes into play that further improves the performance of the charcoal and the biochar systems. High thermal efficiency gives the opportunity to cut down on fuel input, and to optimise the feedstock consumption from a climate perspective. This means that the most harmful fuels or stove-fuel combinations can be avoided, as implemented in the optimised version of the charcoal and the biochar system. Harmful in this context does not only mean polluting in terms of products of incomplete combustion, it also refers to a lack of carbon credits for non-renewable biomass. As the worst performing fuel type, conventional charcoal is the first energy source to be removed. Because of the definition of the improved systems and their energy yield from unprocessed feedstocks being sufficient, conventional charcoal is excluded from the start. The other primary feedstocks show rather small differences in emission factors. However, Acacia wood receives a smaller carbon credit for renewable biomass, which would partly offset its climate impact. Consequently, unsustainably harvested fuels are to be reduced as a priority. Under the current model assumptions, this lowers the consumption of off-farm wood as the only feedstock source that has a non-renewable fraction.

**Choice of feedstocks.** A lower consumption of off-farm wood is not only desirable from a climate perspective and to cut down unsustainable extraction. If the distance to the point of collection rises, people are likely to spend more time to obtain the same amount of feedstocks and to carry heavier loads. Therefore, it is realistic to assume that higher fuel use efficiency reduces the use of off-farm wood as far as possible, even if the farmers are unaware of environmental implications. In contrast, the composition of on-farm feedstock consumption will probably not change in practice, and there are two reasons why the ranking among on-farm biomass is of limited validity. First, the recommendations on which fuels to reduce first draw on assumptions that do not necessarily reflect field conditions. For instance, maize cobs that are not used as a fuel are considered to degrade biologically and release all feedstock carbon as $CO_2$. Therefore, a no-use scenario does not affect the results of this assessment, because the carbon credit for renewable biomass completely offsets the emissions. However, if biodegradation is not entirely aerobic and not all carbon is fully oxidised, the resulting climate impact would need to be balanced against emission savings during cooking.

Second, the ranking of feedstocks does not account for differences and indirect effects that are more relevant for famers' choices, sustainability and eventually even climate change. These include, for instance, mean annual increment, nutrient and water consumption, co-products or additional functions of specific species, and not least economic costs. Starting from private interests, a more realistic approach might be to reduce the fraction of fuel bought on the market at an early stage, at least after off-farm wood. For the sake of sustainability in a broader sense, favouring species that supply energy feedstocks as a by-product or residue might be best, even if they cause higher emissions. An example of such a trade-off are maize cobs which are available as waste material; yet during conversion and combustion, they emit higher proportions of carbon monoxide and particulate matter, leading to indoor air pollution and hazards for human health. Contrarily, Eucalyptus has better fuel properties but has been criticised for its high water and nutrient consumption (Oballa, Konuche, Muchiri, & Kigomo, 2010, p. iii). Several studies show that the fast growing tree species has a greater water use efficiency than native trees (i.e., water consumption in relation to productivity), and that nutrient removal mainly stems from using it as a short rotation crop (Oballa et al., 2010, pp. 14–23). Nevertheless, efficiency does not exempt resource use from competition with other demands, nor from environmental impacts. This is an important constraint to be discussed further in connection with the biochar system.

### 6.1.2 Climate impact, services and health

Despite their importance for implementation, the considerations above reach the limits of LCA's strength to rationally evaluate systems. Besides being difficult to capture quantitatively, the side-effects concern various environmental impact pathways. Comparing these effects on a common basis may avoid trade-offs, but requires value judgements on the relative importance of each impact category (Finnveden et al., 2009). The merits of such an exercise appear low for this study because aggregating the results to a single score does not raise their significance. However, the results of a partial LCA as this one need to be interpreted with care, and considering factors that are not reflected in GWC as a single metric. The following discussion is based on the findings from the upstream model in order to account for opportunities of optimisation; the tendency and conclusions are identical for both modelling approaches.

**Reference versus improved systems.** With the extended pollutant set and $GWP_{20}$, the charcoal and the biochar system save 68% and 86% of the baseline's climate impact, respectively. Using Kyoto gases only and a time horizon of 100 years, the charcoal system reduces the GWC by 75% compared to the baseline. Relative savings of 157% for the biochar system imply that it does not only avoid the baseline's full impact, but it additionally yields a net carbon credit.

**Charcoal versus biochar.** Irrespective of the pollutant set and time horizon, the biochar system has a considerably lower climate impact than the charcoal system. Using the large pollutant set and $GWP_{20}$, it saves 56% of GWC compared to the charcoal system. With Kyoto gases only and a time horizon of 100 years, the discrepancy increases, because the biochar system benefits more strongly from $CO_2$ and carbon sequestration being given a greater weight. Under these settings, the biochar system reduces the GWC by 220%, which means that it provides a net carbon credit that is larger than the charcoal system's total impact.

From a climate perspective, the choice of the best alternative is unambiguous. The strength of the biochar system lies on the one hand in avoiding char combustion in the KCJ, which is more polluting in relation to net energy than cooking with the gasifier, irrespective of the feedstock. On the other hand, the relatively small climate impact from the TLUD stove is partly or entirely offset by carbon sequestration, depending on pollutant set and time frame. The optimised biochar system delivers 789 kg of char per year on a wet mass basis, which is equivalent to 735 kg on a dry mass basis with an average carbon content of 770 g/kg. Assuming that these 566 kg carbon have a recalcitrant fraction of 80% (Whitman et al., 2010), 32 kg carbon are sequestered for each GJ net energy provided by the gasifier. The findings from both modelling approaches are in line with the results of other authors assessing pyrolytic cook stoves in Kenyan smallholder farming. Torres (2011) and Whitman et al. (2011) report an annual biochar production capacity of 0.5-1 tonnes per farm from a similar amount of primary feedstocks, and Lehmann et al. (2006) calculate a carbon sequestration rate of 30.6 kg per GJ energy produced.

**Biochar as a soil amendment.** When used as a soil amendment, biochar does not only store its 80% recalcitrant carbon, but also improves soil properties. As laid out by Sohi et al. (2010, pp. 70–72), putting char to soil has various direct and indirect effects on the greenhouse gas balance; examples include lower fertilizer production and irrigation, reduced land conversion, suppression of emissions from soil, and higher plant productivity. These factors are not quantified in this assessment, since their relative importance for the total GHG balance is estimated between 0 and 5% (Scholz et al., 2014, pp. 34–35). While biochar has proven to increase water and nutrient availability for agricultural crops, the effect on plant growth and yield depends foremost on soil, biochar and crop type; the previous water and nutrient status; and not least the rate of application (Sohi et al., 2010, pp. 67–70). A meta-analysis spanning 86 biochar treatments on a range of soil and crop types found that biochar application mostly increases productivity, although it may also have a negative impact; in either way, there is no linear relationship between application rate and yield gains (Verheijen et al., 2010, p. 91). The study's grand mean of 10% higher plant productivity draws on application rates between 1.5 tons and over 100 tons per hectare, whereas other authors observed that comparatively low biochar inputs can more than double the yield, especially on highly weathered tropical soils under fertilisation (Scholz et al., 2014, p. 28).

To evaluate the agronomic effect of biochar, the Biochar Project runs pot trials over several seasons with soil types from different regions in Kenya. During the first season, the experiments on soil samples from Eastern Kenya found 1 tonne of biochar per hectare to be effective under NPK fertilisation (i.e., nitrogen, phosphorus, and potassium). Since lower application rates than 1 t/ha were not tested, the "efficient dose" needs to lie within the range of 0-1 t/ha. A dose of more than 1 t/ha did not further increase plant productivity on the fertilised samples. Without fertilisation, a higher application rate of 5 t/ha led to additional gains. Yet compared to the first tonne, the marginal yield increase was smaller. The results reported here have not been unpublished yet, and it is important to note that the benefits observed during the first season may differ from the long-term effects. The analysis of the samples from the second season is still ongoing, but preliminary results have shown that the effects are not the same as in the first season.

The model farm has 0.95 hectares of land, which is not entirely used to grow biomass. Conservatively, the full area is assumed to be treated with biochar. With an annual char yield of 789 kg in the improved biochar system, the dosage per hectare of farm land can be up to 831 kg of biochar per year. The fact that biochar remains stable over decades or even centuries makes it likely that its positive agronomic effects also persist, at least for several growing seasons. However, there is a lack of long-term studies that would substantiate this assumption in quantitative terms. The mean residence time of 500 years for the recalcitrant fraction of biochar refers to carbon sequestration and is not directly transferable to agronomic benefits. In agricultural soils under intense cultivation, tillage, erosion and leaching are the main causes for losses in biochar, whereas biological decomposition plays a minor role (Scholz et al., 2014, p. 42). Within two years after application, measurements in a savanna region of Colombia observed that only 2% of the applied biochar was decomposed, but 45% was eroded, most notably with surface runoff during intense precipitation (Major, Lehmann, Rondon, & Goodale, 2010; Scholz et al., 2014, p. 42). While biological decomposition might be higher in the tropics, surface runoff is probably lower and justifies the conservative assumption that half of the biochar applied is lost after two years. If the loss of 208 kg biochar is replaced annually, the char yield of the improved biochar system allows to keep the permanent rate of soil amendment at 3.3 tonnes per hectare.

**Health.** In the context of improved cook stoves, emissions of carbon monoxide and particulate matter inside of unvented homes are a major concern. Compared to traditional wood stoves, charcoal combustion is known to release up to the threefold amount of CO during the same cooking task, whilst cutting PM emissions by 80% (MacCarty, Still, & Ogle, 2010). The results of this assessment fit into that picture, although the increase in CO is rather small. This is mainly because MacCarty et al. (2010) tested traditional charcoal stoves that consume as much energy as wood stoves, whereas the Kenya Ceramic Jiko is considered to have double the thermal efficiency of the three-stone fire in the present study. Cooking with the gasifier during char production is by far the cleanest option. By separating the two phases of combustion, the TLUD stove achieves a higher level of complete combustion. In relation to the three-stone fire, it reduces CO and PM emissions by more than 60% and 80%, respectively.

### 6.1.3 Gross energy consumption

Both improved systems significantly reduce the model farm's need for biofuels. In order to account for the higher energy density of charcoal, this difference is better expressed in terms of gross energy than in feedstock mass. Based on the results of the upstream model, the charcoal system has an overall thermal efficiency of 33%, thus lowering gross energy consumption by 60% compared to the baseline. The optimised biochar system only reaches an overall thermal efficiency of 21%, and therefore requires a higher feedstock input than the charcoal system. However, it still saves 36% gross energy in relation to the baseline, which brings the lowest share of energy to the pot, namely 13%.

The fact that the charcoal system performs better than the biochar system regarding thermal efficiency and feedstock input brings a new dimension to the discussion. In a situation of sufficient biomass availability, putting char to soil is clearly the best alternative; not only from a climate perspective but also due to various co-benefits in agriculture and lower health hazards from indoor air pollution. Yet if organic resources are scarce and competition with other demands rises, it might be better to use char for energy and thus save primary feedstocks. In practice, these factors are likely to lead to a combination of both systems. Once harvested and cooled down, the char can be stored and saved for later uses. Depending on biomass availability, energy needs and the current soil status, the farmers can decide how to make best use of the char.

Under extreme conditions, resource scarcity can create a situation where the use of char for energy outperforms putting char to soil in relation to climate. If all feedstocks are assumed to be 100% non-renewable in the upstream model, the biochar system is most affected. It loses not only the credit for emissions from renewable biomass, which similarly happens to the charcoal system, yet at a lower scale in absolute terms. Additionally, biochar from non-renewable biomass does not allow for net carbon sequestration, whilst releasing its fraction of labile carbon. As $CO_2$ from non-renewable biochar is climate relevant, putting char to soil even increases the biochar system's GWC. In comparison, the charcoal system's low feedstock consumption makes it less vulnerable to a rise in unsustainable harvesting. Under a theoretical assumption of 100% NRB, the charcoal system has a lower GWC with all pollutant sets and time frames, apart from the combination of set 2 and $GWP_{20}$ where the biochar system is still slightly better. Looking at the contributions from single pollutants shows how different assessment frameworks shape the results. The main weakness of the biochar system is its large feedstock input; thanks to the relatively clean combustion and conversion process in the TLUD gasifier, this results in high emissions of carbon dioxide. On the contrary, the charcoal system releases considerable fractions of CO and $CH_4$ from char combustion. As the combination of pollutant set 2 and $GWP_{20}$ comparatively puts the lowest weight on $CO_2$, the result for the biochar system slips under the charcoal system's GWC.

To illustrate the diverging impact of increasing non-renewable biomass on the charcoal and biochar system, Figure 34 compares the net climate impact of each system delivering 1 GJ net energy. For the sake of comparability, only Eucalyptus wood is considered, which goes entirely to the three-stone fire in the baseline (i.e., conversion of Eucalyptus to conventional charcoal is excluded). The GWC is calculated with pollutant set 1 and $GWP_{100}$ to illustrate how the charcoal system outperforms the biochar system at a certain share of NRB; under these settings, the threshold lies at 77%. The light lines show the declining credits from the renewable fuel fraction, and also of biochar if applicable. The dashed light lines highlight the large difference between each system's climate impact with and without carbon credits.

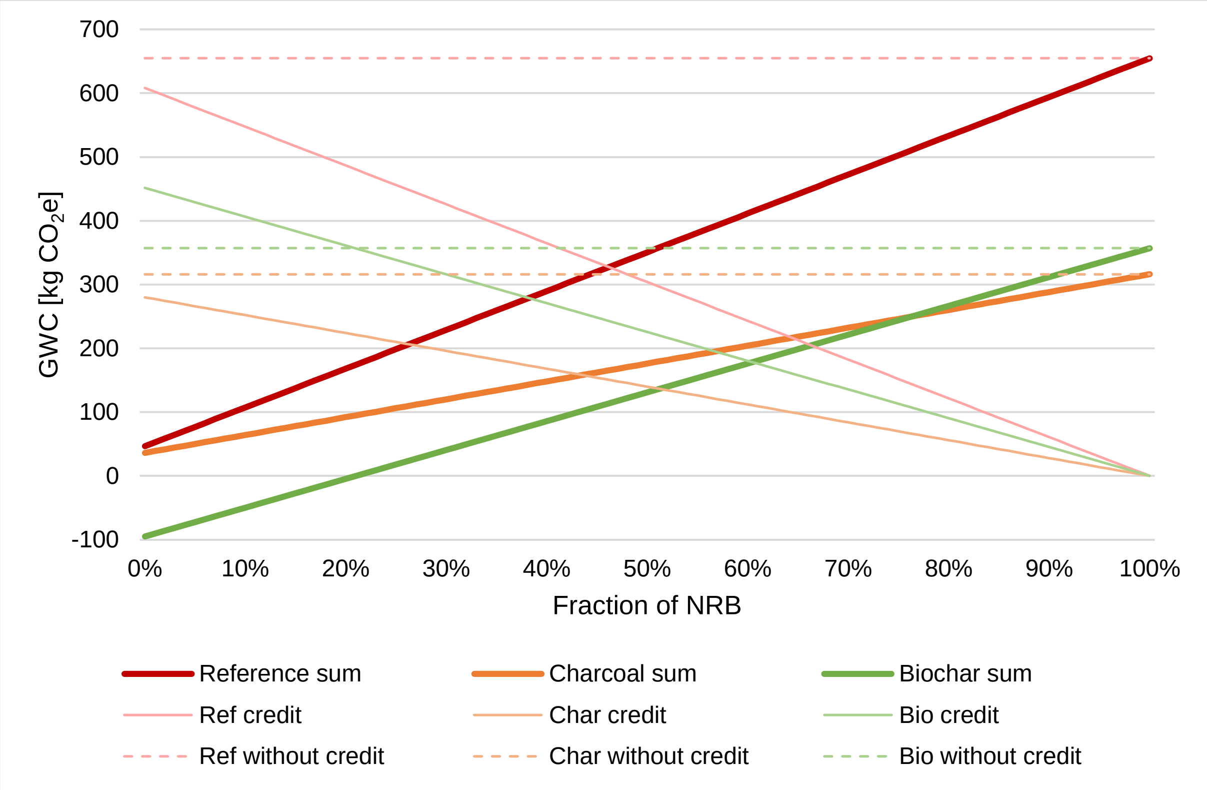


**Figure 34.** Impact of different NRB settings on each system's GWC and carbon credit when supplying 1 GJ net energy from Eucalyptus wood**;** GWC is calculated using set 1 and $GWP_{100}$

## 6.2 Central model parameters and assumptions

**Farm characteristics.** The types and mass of potentially available feedstocks vary greatly by region, since climate and soil type limit or enhance the productive capacity of crops. However, even under similar background conditions, Torres-Rojas et al. (2011) identified three major factors that influence biomass productivity and consequently the capacity to produce biochar: farm size (i.e., lower land availability incentivises productivity), farm age since conversion (i.e., declining soil quality limits productivity) and land allocation to specific crops (i.e., differences in annual increment or yield determine total productivity). Whitman et al. (2011) include farm age as a proxy for soil fertility in the sensitivity analysis, showing that it is important for stocks of soil organic carbon and yield; however, the impact on GHG emissions was negligible. Due to the limited scope and a lack of local data from the Biochar Project, this thesis omits variations due to farm age, size and choice of crops. Instead, it assumes that they are adequately represented by the typical values employed for the model farm.

**Feedstocks.** The surveys suggest that in Manyatta, tree prunings are commonly used as a fuel, whereas maize cobs rather support lighting the fire. Other farm residues such as stovers mainly serve as animal feed or organic fertiliser after composting. The cases where biomass residues are not used for anything are rare. These results lead to the assumption that all material from pruning is available as a fuel in each of the three systems. Maize cobs are considered as an additional feedstock for char-making in the two improved systems. In the reference system, they do not contribute to fuel supply. Due to a lack of more precise data, maize cobs are assumed to be consumed during the lighting process or left for natural decomposition. Other potential feedstocks are omitted in order to avoid conflicts with other functions such as fodder supply or soil protection. Yet, the amount of biomass supplied to the systems can be easily corrected up- or downwards in the parameter sheet of the model. In relative terms, the results are only affected if the shares of specific wood species or the fraction of non-renewable biomass are altered, directly or indirectly (e.g., via the percentages sourced on-farm and off-farm).

**Fraction of non-renewable biomass.** Renewability determines whether the biogenic carbon emitted during combustion or sequestered in biochar is assumed to be equivalently taken up as $CO_2$ during plant regrowth. For simplicity, the fate approach neglects the time lag between the release of climate forcing pollutants to the atmosphere and $CO_2$ assimilation. Addressing this issue requires a dynamic modelling approach, which lies beyond the scope of this thesis but has been addressed by other authors (see, e.g., Ericsson et al., 2013).

**Net carbon sequestration and permanence.** Biochar does not sequester more carbon than bound in the feedstock before harvesting (Whitman et al., 2010). This implies that in absolute terms, biochar produced from unsustainably harvested stocks leads to a net carbon flow to the atmosphere, owing to the losses during conversion and the labile C fraction. It only reaps a net benefit for climate change mitigation if the biomass is renewable and regrows, thereby assimilating additional $CO_2$ from the atmosphere. In this case, the carbon credit comes from converting labile fresh biomass C into a slow-cycling form (Whitman et al., 2010, pp. 90–92). The stability of biochar depends on the carbonisation process as well as on climate and soil conditions (Scholz et al., 2014, pp. 4–43). For simplicity, the model uses values that are well established in the literature, i.e., 80% recalcitrant fraction and 500 years MRT (Whitman et al., 2010).

**Performance of stove fuel combinations.** Throughout the assessment, thermal efficiency and conversion efficiency have proven a strong leverage effect on the level of detrimental emissions. The resulting energy savings materialise strongest in the Global Warming Commitment if non-renewable fuels are displaced. For both quantitative and qualitative emission reductions, assumptions on fuel use in the baseline system are critical (Whitman et al., 2010). Due to a lack of direct measurement results, thermal and conversion efficiency are determined in relation to established values for generic stove-fuel combinations (i.e., 15% for the three-stone fire using wood, and 30% for the Kenya Ceramic Jiko using charcoal). For the KCJ, the project data allow to determine different levels of efficiency, depending on the type of charcoal used. For the gasifier, thermal and conversion efficiency is assumed to be constant for all wood species, although they differ in energy density and power delivered. However, the effect on the results is probably negligible compared to the influence of stove handling and the meal to be cooked.

**Emission factors.** Similar to efficiency, emission factors depend on the power level required to cook a specific meal, and the duration of different power phases throughout the cooking process. While standardised laboratory experiments such as the Water Boiling Test are a poor means to characterise practical stove operation, field tests are usually not comparable (VITA, 1985). Since the emission factors in this assessment draw on several studies with different methods and settings, they involve considerable uncertainty. As a compromise between errors in field-based testing and laboratory experiments lacking practical relevance, the Kitchen Performance Test provides a sufficiently standardised procedure for future assessments. Several studies confirm that reloading the gasifier with fuel leads to spikes in CO emissions (Andreatta, 2007; Jetter et al., 2012; MacCarty et al., 2008; Tryner et al., 2014). This is especially relevant for fuels with a low bulk density; for corn cobs, this factor is incorporated by altering the pollutant ratios according to a rough estimate. If the emission ratios for the TLUD stove from MacCarty et al. (2008) include char combustion (which could not be verified), the levels of CO emissions and other PIC are overestimated. In that case, the factors could be seen as a conservative assumption for the risk that air enters the fuel bed, which leads to a partial oxidation of the char.

The lack of comparability between secondary data as laid out above is only one of several problems. Section 6.3 discusses further largely unavoidable factors that infringe the validity of emission factors. Moreover, the method of obtaining missing emission factors for specific feedstocks from pollutant ratios and carbon balance calculations omits important fuel properties other than contents of C and S from ultimate chemical analysis. Consequently, conclusions from the technology-oriented evaluation of stove-fuel combinations should be drawn with care, considering that individual emission factors involve high uncertainty. When alternatives are compared at a higher level of analysis and single species are embedded in pollutant sets, process chains and systems, the factors are likely to show reliable tendencies.

## 6.3 Remaining uncertainty and limitations

After testing various parameter settings and combinations, the highest uncertainty remains incorporated in the performance indicators and emission factors of each stove-fuel combination. A sensitivity analysis would allow to evaluate the robustness of the results, but appears not feasible within the scope of this research. While the relationship between combustion efficiency, net energy yield and pollutant ratios is too complex for simple assumption-based variations, a lack of comparable data prevents the use of measurement results. Instead, the data analysis has led to the identification of three “biases” that infringe the representativeness of emission factors for the actual stove operation conditions in the field:

1. **The stove operation bias:** The power mode of a cook stove varies by the purpose it is used for, e.g., boiling water or cooking a meal; while standardised testing procedures are hardly able to capture actual operation conditions, the power level (i.e., high power during bringing to boil, low power during simmering) strongly affects the pollutant ratios.
2. **The stove handling bias:** Cooking tests usually follow a standardised procedure of stove handling; this can either lead to an optimised performance that is unrealistic under field conditions, or to pessimistic assumptions on the adaptive capacity of farmers, e.g., to adjust the type and amount of fuel used according to the meal to be cooked.
3. **The feedstock bias:** Biomass is far from having uniform fuel properties, not even when it is further broken down into feedstock types (e.g., wood or crop residues) or species (e.g., *Grevillea robusta* or Acacia); factors such as energy and moisture content, bulk density and chemical composition further vary with parts of the tree used (e.g., stem and branch wood, twigs and prunings, bark), climate, season, and habits of the user.
4. **The useful energy bias.** Thermal efficiency is defined as the ratio of energy reaching the pot contents to energy input. Consequently, any other energy uses such as lighting or space heating are considered unproductive, although in practice, they do constitute a reason why farmers light, e.g., the three-stone fire.

In a similar context of assessment, Scholz et al. (2014, pp. 172–173) ran a sensitivity analysis on the methane emissions from using 1 kg of wood in the three-stone stove or the gasifier. For both stoves, the results indicate that within the uncertainty range, methane does not dominate the overall performance of the systems. The large range of factors reported in the literature (i.e., between 0.6 and 6.4 kg methane per kg feedstock in the three-stone stove) emphasises how different experimental procedures affect the measurement results, leading to high data variability even for well tested technologies.

**Options for improvement.** The “biases” laid out above reflect that feedstock consumption and emissions from cooking depend on various context-specific factors. This suggests that stove technology is not the only approach to increase efficiency. Other measures that do not involve investment costs for a new device might be as effective and perhaps easier to implement. Some of the steps proposed below are inherently included in the improved strategies, being partly responsible for their good performance. Yet, each of them could be added to any of the systems independently in order to “pick the low hanging fruits” before introducing new devices. Measures to save energy and reduce emissions include (Jetter et al., 2012; Kituyi & Kirubi, 2003; MoE, 2002, pp. 56–59; Partnership for Clean Indoor Air, 2012, p. 69):

- adapt food preparation to shorten cooking time (e.g., pre-soaking, chopping into smaller pieces);
- use wide-bottomed pots to optimise the heat transfer;
- cover the vessel during cooking to reduce heat losses;
- maximise the share of productive energy by "multiple cooking" (e.g., use a single fire to cook several meals, or to cook and heat water for washing);
- foster on-farm trees and agroforestry to reduce off-farm sourcing;
- develop unconventional biomass fuels (e.g., largely unused residues such as maize cobs, coffee husks or sawdust);
- prepare the feedstocks to increase combustion efficiency (e.g., chopping into smaller pieces, drying feedstocks);
- improve stove handling (e.g., careful fire tending, continuous feeding, extinguishing the fire immediately when the cooking task is completed); and
- increase ventilation to lower CO and PM concentrations in indoor air (e.g., cut a small covered hole in the roof to minimise heat losses whilst removing the smoke that collects near the ceiling).

**Emission set and time frame.** As laid out in section 3.3, the two pollutant sets and time frames both have advantages and drawbacks, making it impossible to decide what is "more relevant". On the one hand, pollutant set 1 with $GWP_{100}$ is well-established, sufficiently certain and suited to the long-term perspective of this study. On the other hand, the combination only depicts a small proportion of the impact following form incomplete combustion. Though considerably more uncertain, pollutant set 2 covers most problematic pollutant species, and captures atmospheric interactions more comprehensively. Therefore, set 2 always finds a higher climate impact than set 1. Set 2 is combined with $GWP_{20}$ in order to assess short-lived gases in a period suitable to their lifetime. For gases having a shorter lifetime than $CO_2$, the characterisation factor increases with decreasing time horizon, and vice versa for gases with longer lifetimes (Fuglestvedt et al., 2003). Consequently, the choice of time horizon determines the weighting of long and short-lived substances. Gains or losses in relative performance depend on the PIC to $CO_2$ ratio of each stove-fuel combination.

**Timing.** When bioenergy systems are to be assessed, the IPCC baseline model shows considerable shortcomings. As a cumulative metric, the GWP does not account for the timing of emissions and the subsequent lifetime of pollutants in the characterisation factor. This means that the time lag between the emission of $CO_2$ to the atmosphere and its removal by means of photosynthesis, loss or deposition is ignored, alongside the radiative forcing caused by the molecules. Several authors have made attempts to depict time-dependent carbon fluxes and interactions with the carbon cycle (i.e., temporary carbon sequestration, storage in biomass and soil organic carbon pools) in LCA (see Ericsson et al., 2013). However, potential solutions such as time-adjusted or dynamic modelling lie beyond the scope of this thesis.

**Climate neutrality.** Furthermore, the simplified approach of dividing the biomass consumption into a renewable and thus "climate neutral" and a non-renewable share assumes that energy crops are established, grown and harvested at zero emissions. Whilst this would trigger considerable distortion in intensively managed and used systems, the effects are negligible in sub-Saharan low-tech farming and forestry. Even if biomass originates from more intense production (i.e., farming or commercial forestry), the supply consists of residues of food or timber production. The marginal resources used as energy feedstocks by smallholder farmers are not assigned any impacts from production in this study.

# 7 Summary and conclusions

Comparing different strategies of biofuel management for smallholder farmers in Kenya, this thesis demonstrates the benefits of char-producing cook stoves in relation to energy security, health, soil quality and climate change mitigation. Irrespective of the modelling approach and even under the least favourable parameter settings, the charcoal and the biochar system show clear advantages over the traditional practices. The main distinctive feature is that both improved systems replace open combustion and the use of conventional charcoal by a top-lit updraft gasifier. Combining cooking with char production, this stove is not only more efficient in providing thermal energy, but also delivers a carbon- and energy-rich co-product.

Throughout the assessment, stove efficiency has proven a strong leverage effect on the level of detrimental emissions. While cleaner combustion leads to qualitative emission reductions, a lower feedstock input allows for quantitative savings. If higher fuel use efficiency displaces non-renewable biomass, the emission abatement materialises even stronger in the Global Warming Commitment. Overall, the results leave no doubt about the gains in relation to the baseline, yet there are trade-offs between using char for energy or as a soil amendment.

The strengths of the biochar system lie in

- avoiding char combustion in the Kenya Ceramic Jiko, which is more polluting in relation to net energy than cooking with the gasifier, irrespective of the feedstock;
- offsetting the gasifier's relatively small climate impact partly or entirely by carbon sequestration, depending on pollutant set and time frame; 32 kg carbon are stored in soil for each GJ net energy provided by the gasifier; and
- delivering 789 kg of biochar per year.

In contrast, the charcoal system

- has an overall thermal efficiency of 33%, thus lowering gross energy consumption by 60% compared to the baseline, and by 37% compared to the biochar system; and
- offers the opportunity to displace all unsustainably harvested feedstocks, leading to 0% non-renewable biomass in the fuel mix.

With the extended pollutant set and $GWP_{20}$, the charcoal and the biochar system save 68% and 86% of the baseline's climate impact, respectively. Using Kyoto gases only and a time horizon of 100 years, the charcoal system reduces the climate impact by 75% compared to the baseline. Relative savings of -157% for the biochar system imply that it even yields a net carbon credit. Comparing the two improved systems shows that in relative terms, the biochar system gains most from assessing Kyoto gases only with $GWP_{100}$. Under these settings, carbon sequestration is given the greatest weight in relation to other pollutant species than $CO_2$.

The fact that the charcoal system performs better than the biochar system regarding thermal efficiency and feedstock consumption brings an interesting dimension to the evaluation. In a situation of sufficient biomass availability, putting char to soil is clearly the best alternative; not only from a climate perspective but also due to various co-benefits in agriculture and lower health hazards from indoor air pollution. Yet if organic resources are scarce and competition with other demands rises, it may be better to use char for energy and thus save primary feedstocks. On the other hand, applying biochar to soil in resource poor regions has a higher potential to benefit plant productivity. In practice, these factors are likely to lead to a combination of both systems. Once harvested and cooled down, the char can be stored and saved for later uses. Depending on biomass availability, energy needs and the current soil status, the farmers can decide how to make best use of the char. These factors vary between seasons for each farmer, and between regions on a larger geographical scale.

**Potential for application.** The benefits that smallholders can realise from either of the two strategies of improved biofuel use depend on factors that lie beyond what this assessment can accomplish. On the one hand, the implementation at individual farms will be less uniform and guided by rational choices than the settings and assumptions in LCA. On the other hand, there are many more factors coming into play, and the farmers' adaptive capacity might lead to new solutions. In the Biochar Project, the adoption study for gasifiers has shown that daily chores, food preferences and cooking habits have a strong influence on households' energy use patterns. For instance, the fact that cooking with co-production of char in the TLUD gasifier takes additional time for feedstock preparation, lighting and harvesting the char resulted in 70% of the farmers using the stove in the evening. Overall, only 35% of the households used the gasifier on a daily basis, and all participants preferred to cook quicker meals with it in order to avoid refilling the stove with fuel. These findings point out clear limitations to the biochar system, which relies on the gasifier as the only stove. Besides, the tendency to add modern solutions to traditional practices instead of replacing them fits into the picture of "fuel stacking", which has repeatedly come up during the implementation of programmes promoting improved cook stoves.

**Methodological considerations.** Pivot tables and charts in Excel with their numerous options to process and display the data proved to be a powerful tool to analyse a large set of parameters and variations. Within a reasonable time, the model allows to explore many scenarios and to switch between different settings in the assessment framework. Thereby, it automatically integrates robustness checks at an early stage of analysis. Most notably, using different pollutant sets and time horizons for the Global Warming Potential has a high impact on the results in absolute terms. Moreover, the fraction of non-renewable biomass determines the credit for emissions from renewable biomass and for carbon sequestration. Testing all possible combinations for each system on several levels of analysis (i.e., the system level, the level of process chains, and the level of stove-fuel combinations) is nearly impossible to handle in individual calculations. Therefore, the model combines bottom-up calculations from single pollutant species with pivot tables to aggregate the results to the desired level, and to filter the data of interest.

In its basic application, Life Cycle Assessment is used to evaluate well-defined products or services. Explorative LCA studies that test several scenarios or assumptions are comparatively rare. While pivot tables seem to be unconventional in current LCA applications, they certainly merit greater attention for discrete parameter variation (i.e., what-if calculations) or testing different methodological choices.

**Opportunities for further research.** The highest uncertainty remains incorporated in the performance indicators and emission factors of each stove-fuel combination. In order to address the four "biases" that hamper their representativeness for actual stove operation in the field, comparable tests with each stove-fuel combination are needed, covering a comprehensive pollutant set, measuring emissions instead of concentrations, and representing average cooking or stove use practices rather than a single meal. For the Biochar Project in particular, it is important to establish robust performance indicators and emission factors for the TLUD gasifier. Currently, no literature data are available to adequately characterise the char-producing cook stove as the central element of the improved systems. Existing studies either cover too few pollutant species, report only concentrations, or combust the char directly in the gasifier.

From a methodological point of view, a dynamic modelling approach would be interesting to account for changes in plant productivity and available feedstocks. The climate impact of biofuels could be captured more accurately in a time-dependent model that considers the period between the release of climate forcing agents and assimilation, or the short-term storage of labile carbon.

Overall, the case study on Kenyan smallholder farmers illustrates that the combination of biofuels and poor stove technology is far from being climate neutral. Placed at the nexus of energy, health and soil, the use of farm-level organic resources is a sensitive issue for peoples' livelihoods. If multiple goals are at stake, e.g., mitigation of climate impacts, health protection, energy security, food production, and more sustainable resource management in general, decision making gets particularly complex. In this context, the findings of this thesis provide guidance on leverage points for qualitative and quantitative emission reductions. Moreover, the sensitivity analysis reveals critical parameter settings that affect the relative performance of the systems. Taking into account other factors than climate change, the thesis finds a balance between the strict LCA framework and a more practice-oriented evaluation. Thereby, it fits well into the transdisciplinary approach of the Biochar Project, where socio-economic and cultural factors merit as much attention as technology assessment.

# 8 References

Achour, N. (2015). *Evaluating energy efficiency and emissions of charred biomass used as a fuel for household cooking in rural Kenya* (Master thesis). Swedish University of Agricultural Sciences, Uppsala.

Adam, J. C. (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort-kiln (Eco-charcoal). *Renewable Energy*, *34*(8), 1923–1925. doi:10.1016/j.renene.2008.12.009

AfDB. (2014). *Kenya: Country strategy paper 2014-2018*. Abidjan: African Development Bank Group. Retrieved from http://www.afdb.org/en/documents/publications/

Altieri, M. A., Funes-Monzote, F. R., & Petersen, P. (2012). Agroecologically efficient agricultural systems for smallholder farmers: Contributions to food sovereignty. *Agronomy for Sustainable Development*, *32*(1), 1–13. doi:10.1007/s13593-011-0065-6

Alvum-Toll, K., Karlsson, T., & Ström, H. (2011). *Biochar as soil amendment. A comparison between plant materials for biochar production from three regions in Kenya* (Bachelor thesis). Swedish University of Agricultural Sciences, Uppsala.

Andreatta, D. (2007). *A report on some experiments with the top-lit up draft (TLUD) stove*. Presented at the ETHOS 2007 Conference, Kirkland, Washington (27 January 2007). Retrieved from http://www.bioenergylists.org/stovesdoc/Andreatta/TLUD_Report.pdf

Antal, M. J., Croiset, E., Dai, X., DeAlmeida, C., Mok, W. S.-L., Norberg, N.,. . . Al Majthoub, M. (1996). High-yield biomass charcoal. *Energy & Fuels*, *10*(3), 652–658. doi:10.1021/ef9501859

Åslund, I. (2012). *Effects of applying biochar to soils from Embu, Kenya. Effects on crop residue decomposition and soil fertility under varying soil moisture levels* (Bachelor thesis). Swedish University of Agricultural Sciences, Uppsala.

Bai, Z., & Dent, D. (2006). *Global assessment of land degradation and improvement: Pilot study in Kenya*. Report 2006/01. Wageningen: ISRIC – World Soil Information. Retrieved from http://isric.org/isric/webdocs/docs/ISRIC_Report_2006_01.pdf

Bailis, R., Cowan, A., Berrueta, V., & Masera, O. (2009). Arresting the killer in the kitchen: The promises and pitfalls of commercializing improved cookstoves. *World Development*, *37*(10), 1694–1705. doi:10.1016/j.worlddev.2009.03.004

Bailis, R., Ezzati, M., & Kammen, D. M. (2003). Greenhouse gas implications of household energy technology in Kenya. *Environmental Science & Technology*, *37*(10), 2051–2059. doi:10.1021/es026058q

Bailis, R., Smith, K., & Edwards, R. (2007). *Kitchen Performance Test (KPT)*. Household Energy and Health Programme, Shell Foundation. Retrieved from https://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/83-1.pdf

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J.,. . . Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. doi:10.1002/jgrd.50171

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., & Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research*, *109*(D14203), 1–43. doi:10.1029/2003JD003697

Bond, T. C., Zarzycki, C., Flanner, M. G., & Koch, D. M. (2011). Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. *Atmospheric Chemistry and Physics*, *11*(4), 1505–1525. doi:10.5194/acp-11-1505-2011

De Groote, H., Owuor, G., Doss, C., Ouma, J., Muhammad, L., & Danda, K. (2005). The maize green revolution in Kenya revisited. *Electronic Journal of Agricultural and Development Economics (eJADE)*. (2), 32–49. Retrieved from ftp://ftp.fao.org/docrep/fao/008/ae692e/ae692e00.pdf

Drigo, R., Bailis, R., Ghilardi, A., & Masera, O. (2015). *WISDOM Kenya: Analysis of woodfuel supply, demand and sustainability in Kenya*. Tier 2 Report. GACC Yale-UNAM Project "Geospatial Analysis and Modeling of Non-Renewable Biomass: WISDOM and beyond". Retrieved from http://www.wisdomprojects.net/pdf?file=WISDOM_Kenya_report_Drigo_et_al_June2015.pdf

ECN. (2016). *Phyllis2: Database for biomass and waste*: Energy research Centre of the Netherlands. Retrieved from https://www.ecn.nl/phyllis2

Enders, A., Hanley, K., Whitman, T., Joseph, S., & Lehmann, J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology*, *114*, 644–653. doi:10.1016/j.biortech.2012.03.022

Ericsson, N., Porsö, C., Ahlgren, S., Nordberg, Å., Sundberg, C., & Hansson, P.-A. (2013). Time-dependent climate impact of a bioenergy system - methodology development and application to Swedish conditions. *GCB Bioenergy*, *5*(5), 580–590. doi:10.1111/gcbb.12031

European Commission. (2010). *International reference life cycle data system (ILCD) handbook: General guide for Life Cycle Assessment – detailed guidance*. *EUR: 24708 EN*. Luxembourg: Publications Office of the European Union. Retrieved from http://eplca.jrc.ec.europa.eu/?page_id=86

European Commission. (2015). *ELCD 3.2: LCI data set from the European reference Life Cycle Database*. Released in February 2015. Brussels: European Commission. Retrieved from http://eplca.jrc.ec.europa.eu/

FAO. (1983). *Wood fuel surveys*. Forestry for local community development programme. Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/q1085e/q1085e00.htm

FAO. (2015a). *AQUASTAT: Irrigation and drainage*. Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/nr/water/aquastat/irrigationdrainage/index.stm

FAO. (2015b). *FAOSTAT*. Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://faostat3.fao.org

FAO. (2015c). *Global forest resources assessment 2015: Desk reference*. Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a-i4808e.pdf

Fife, D., & Mendoza, J. (2010). Central tendency measures. In I. B. Weiner & W. E. Craighead (Eds.), *The Corsini encyclopedia of psychology* (4th ed., pp. 289–291). Hoboken, N.J.: Wiley & Sons, Inc.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S.,. . . Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. doi:10.1016/j.jenvman.2009.06.018

Fuglestvedt, J. S., Berntsen, T. K., Godal, O., Sausen, R., Shine, K. P., & Skodvin, T. (2003). Metrics of climate change: Assessing radiative forcing and emission indices. *Climatic Change*, *58*(3), 267–331. doi:10.1023/A:1023905326842

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A.,. . . Waitz, I. A. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, *44*(37), 4648–4677. doi:10.1016/j.atmosenv.2009.04.044

Fuwape, J. A., & Akindele, S. O. (1997). Biomass yield and energy value of some fast-growing multipurpose trees in Nigeria. *Biomass and Bioenergy*, *12*(2), 101–106. doi:10.1016/S0961-9534(96)00061-X

Gadi, R., Kulshrestha, U. C., Sarkar, A. K., Garg, S. C., & Parashar, D. C. (2003). Emissions of SO2 and NOx from biofuels in India. *Tellus B*, *55*(3), 787–795. doi:10.1034/j.1600-0889.2003.00065.x

Gathui, T., Mugo, F., Ngugi, W., Wanjiru, H., & Kamau, S. (2011). *The Kenya charcoal policy handbook: Current regulations for a sustainable charcoal sector*. Policy handbook prepared for PISCES. Nairobi: Practical Action Consulting East Africa. Retrieved from http://r4d.dfid.gov.uk/PDF/Outputs/PISCES/Kenya-Charcoal-Policy-Handbook.pdf

Gaur, S., & Reed, T. B. (1995). *An atlas of thermal data for biomass and other fuels*. Technical report prepared for the U.S. Department of Energy. Golden, CO: National Renewable Energy Laboratory.

Gitau, J. K., & Njenga, M. (2015). *Adoption of gasifier cook stoves at Kibugu, Embu county*. Internal project report. Nairobi: World Agroforestry Centre.

Global Alliance for Clean Cookstoves. (2014). *The Water Boiling Test: Cookstove emissions and efficiency in a controlled laboratory setting*. Version 4.2.3, released in March 2014. Retrieved from http://cleancookstoves.org/technology-and-fuels/testing/protocols.html

GoK. (2012). *National climate change action plan – adaptation*. Technical analysis report. Nairobi: Government of Kenya. Retrieved from http://www.kccap.info/

GoK. (2013). *National climate change action plan 2013-2017*. Executive summary. Nairobi: Government of Kenya. Retrieved from http://www.kccap.info/

Grieshop, A. P., Marshall, J. D., & Kandlikar, M. (2011). Health and climate benefits of cookstove replacement options. *Energy Policy*, *39*(12), 7530–7542. doi:10.1016/j.enpol.2011.03.024

Gulyurtlu, I., Penha, E., & Cabrita, I. (1997). Co-combustion of forestry biomass with tyres in a circulating fluidised bed combustor. In A. V. Bridgwater & D. G. B. Boocock (Eds.), *Developments in thermochemical biomass conversion* (pp. 1346–1357). Dordrecht: Springer Netherlands.

Hardin, G. (1968). The tragedy of the commons. *Science*, *162*(3859), 1243–1248. doi:10.1126/science.162.3859.1243

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H.,. . . Mackinnon, J. L. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *369*(1639), 1–12. doi:10.1098/rstb.2013.0089

Hayes, P., & Smith, K. R. (Eds.). (1993). *The global greenhouse regime: Who pays?* London: Earthscan.

Heard, J., Cavers, C., & Adrian, G. (2006). Up in smoke – nutrient loss with straw burning. *Better Crops*, *90*(3), 10–11.

Helander, H., & Larsson, L. (2014). *Emissions and energy use efficiency of household biochar production during cooking in Kenya* (Bachelor thesis). Uppsala University, Uppsala.

Huangfu, Y., Li, H., Chen, X., Xue, C., Chen, C., & Liu, G. (2014). Effects of moisture content in fuel on thermal performance and emission of biomass semi-gasified cookstove. *Energy for Sustainable Development*, *21*, 60–65. doi:10.1016/j.esd.2014.05.007

IEA. (2006). *World energy outlook 2006*. Paris: Organisation for Economic Co-operation and Development and International Energy Agency. Retrieved from http://www.worldenergyoutlook.org/publications/2008-1994/

IEA. (2012). *World energy outlook 2012*. Paris: Organisation for Economic Co-operation and Development and International Energy Agency. Retrieved from http://www.worldenergyoutlook.org/weo2012/

IEA. (2013). *$CO_2$ emissions from fuel combustion*. 2013 edition. Paris: Organisation for Economic Co-operation and Development and International Energy Agency. Retrieved from http://data.iea.org/ieastore/statslisting.asp

Iiyama, M., Chenevoy, A., Otieno, E., Kinyanjui, T., Ndegwa, G., Vandenabeele, J.,. . . Johnson, O. (2014). *Achieving sustainable charcoal in Kenya: Harnessing the opportunities for cross-sectoral integration*. Technical brief. Nairobi: World Agroforestry Centre and Stockholm Environment Institute. Retrieved from http://outputs.worldagroforestry.org/

Institute of Economic Affairs. (2015). *Situational analysis of energy industry, policy and strategy for Kenya*. Nairobi: Institute of Economic Affairs. Retrieved from https://www.africaportal.org/dspace/articles/situational-analysis-energy-industry-policy-and-strategy-kenya

IPCC. (2007). *Climate change 2007: The physical science basis*. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf

IPCC. (2013). *Climate change 2013: The physical science basis*. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_ALL_FINAL.pdf

ISO. (2006a). *ISO 14040:2006: Environmental management – Life Cycle Assessment – principles and framework*. Genève: International Organizational for Standardization. Retrieved from http://www.iso.org/iso/catalogue_detail?csnumber=37456

ISO. (2006b). *ISO 14044:2006: Environmental management - Life Cycle Assessment - requirements and guidelines*. Genève: International Organizational for Standardization. Retrieved from http://www.iso.org/iso/catalogue_detail?csnumber=38498

Jaetzold, R., Smidt, H., Hornet, Z. B., & Shisanya, C. A. (2006). *Farm management handbook of Kenya: Vol. II/C – Natural conditions and farm management information East Kenya* (2nd ed.). Nairobi: Ministry of Agriculture, Republic of Kenya in cooperation with the German Agency for Technical Cooperation (GTZ). Retrieved from http://library.wur.nl/isric/fulltext/isricu_i00023898_001.pdf

Jain, R. (1999). Fuelwood characteristics of selected indigenous tree species from central India. *Bioresource Technology*, *68*(3), 305–308. doi:10.1016/S0960-8524(98)00173-4

Jetter, J., Zhao, Y., Smith, K. R., Khan, B., Yelverton, T., Decarlo, P., & Hays, M. D. (2012). Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environmental Science & Technology*, *46*(19), 10827–10834. doi:10.1021/es301693f

Johnson, M., Edwards, R., Ghilardi, A., Berrueta, V., Gillen, D., Frenk, C. A., & Masera, O. (2009). Quantification of carbon savings from improved biomass cookstove projects. *Environmental Science & Technology*, *43*(7), 2456–2462. doi:10.1021/es801564u

Kabubo-Mariara, J., & Karanja, F. K. (2007). The economic impact of climate change on Kenyan crop agriculture: A Ricardian approach. *Global and Planetary Change*, *57*(3-4), 319–330. doi:10.1016/j.gloplacha.2007.01.002

Karekezi, S., & Turyareeba, P. (1995). Woodstove dissemination in Eastern Africa – a review. *Energy for Sustainable Development*, *1*(6), 12–19. doi:10.1016/S0973-0826(08)60094-0

Kaygusuz, K. (2011). Energy services and energy poverty for sustainable rural development. *Renewable and Sustainable Energy Reviews*, *15*(2), 936–947. doi:10.1016/j.rser.2010.11.003

Kees, M., & Feldmann, L. (2011). The role of donor organisations in promoting energy efficient cook stoves: Clean Cooking Fuels and Technologies in Developing Economies. *Energy Policy*, *39*(12), 7595–7599. doi:10.1016/j.enpol.2011.03.030

Kigomo, N. B. (2001). *State of forest genetic resources in Kenya*. Sub-Regional Workshop FAO/IPGRI/ICRAF on the conservation, management, sustainable utilisation and enhancement of forest genetic resources in Sahelian and North-Sudanian Africa (Ouagadougou, Burkina Faso, 22-24 September 1998). *Forest Genetic Resources Working Papers: Working Paper FGR/18E*. Rome: Forestry Department, Food and Agriculture Organization of United Nations.

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S.,. . . Pell, A. N. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, *11*(5), 726–739. doi:10.1007/s10021-008-9154-z

Kituyi, E., & Kirubi, C. (2003). Influence of diet patterns on fuelwood consumption in Kenyan boarding schools and implications for data and energy policies. *Energy Conversion and Management*, *44*(7), 1099–1109. doi:10.1016/S0196-8904(02)00105-X

Kituyi, E., Marufu, L., Huber, B., Wandiga, S., O. Jumba, I., O. Andreae, M., & Helas, G. (2001a). Biofuel consumption rates and patterns in Kenya. *Biomass and Bioenergy*, *20*(2), 83–99. doi:10.1016/S0961-9534(00)00072-6

Kituyi, E., Marufu, L., Wandiga, S., O. Jumba, I., O. Andreae, M., & Helas, G. (2001b). Biofuel availability and domestic use patterns in Kenya. *Biomass and Bioenergy*, *20*(2), 71–82. doi:10.1016/S0961-9534(00)00071-4

KNBS. (2006). *Kenya integrated household budget survey 2005/06*. Basic report. Nairobi: Kenya National Bureau of Statistics, Ministry of Planning and National Development, Republic of Kenya. Retrieved from http://www.knbs.or.ke/

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, *17*(2), 197–209. doi:10.1002/ldr.696

Lehmann, J., Czimczik, C., Laird, D., & Sohi, S. (2009). Stability of biochar in soil. In S. Joseph & J. Lehmann (Eds.), *Biochar for environmental management. Science and technology* (pp. 183–206). London: Earthscan.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems: A review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 395–419. doi:10.1007/s11027-005-9006-5

Lehmann, J., & Joseph, S. (2009). Biochar for environmental management: An introduction. In S. Joseph & J. Lehmann (Eds.), *Biochar for environmental management. Science and technology* (pp. 1–12). London: Earthscan.

Levasseur, A. (2015). Climate change. In M. Hauschild & M. A. J. Huijbregts (Eds.), *LCA compendium – the complete world of Life Cycle Assessment. Life cycle impact assessment* (pp. 39–50). Dordrecht: Springer.

MacCarty, N., Ogle, D., Still, D., Bond, T., & Roden, C. (2008). A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy for Sustainable Development*, *12*(2), 56–65. doi:10.1016/S0973-0826(08)60429-9

MacCarty, N., Still, D., & Ogle, D. (2010). Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development*, *14*(3), 161–171. doi:10.1016/j.esd.2010.06.002

Magnusson, A. (2015). *Improving small-scale agriculture and countering deforestation. The case of biochar and biochar producing stoves in Embu county, Kenya* (Bachelor thesis). Lund University, Lund.

Mahmoud, Y., Röing de Nowina, K., Sundberg, C., & Njenga, M. (forthcoming). *Potential socio-economic impacts of biochar on smallholder farmers in Kenya*. Submitted manuscript.

Major, J., Lehmann, J., Rondon, M., & Goodale, C. (2010). Fate of soil-applied black carbon: Downward migration, leaching and soil respiration. *Global Change Biology*, *16*(4), 1366–1379. doi:10.1111/j.1365-2486.2009.02044.x

MoE. (2002). *Study on Kenya's energy demand, supply and policy strategy for households, small scale industries and service establishments*. Final report submitted by Kamfor Company Limited. Nairobi: Ministry of Energy, Republic of Kenya.

MoE. (2014). *Draft national energy policy*. Nairobi: Ministry of Energy and Petroleum, Republic of Kenya. Retrieved from http://www.energy.go.ke/downloads/National%20Energy%20Policy%20-%20Final%20Draft.pdf

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *PNAS - Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19680–19685. doi:10.1073/pnas.0701855104

Mugo, F., & Gathui, T. (2010). *Biomass energy use in Kenya*. A background paper prepared for the International Institute for Environment and Development (IIED). Nairobi: Practical Action Consulting East Africa. Retrieved from http://pubs.iied.org/pdfs/G02985.pdf

Mutimba, S., & Barasa, M. (2005). *National charcoal survey: Exploring the potential for a sustainable charcoal industry in Kenya*. Summary report. Nairobi: Energy for Sustainable Development Africa.

NEMA. (2009). *Kenya National Environment Action Plan: Framework 2009-2013*. Nairobi: National Environment Management Authority, Ministry of Environment and Mineral

Resources, Republic of Kenya. Retrieved from http://theredddesk.org/countries/plans/national-environment-action-plan-kenya-2009-2013

Neufeldt, H., Langford, K., Fuller, J., Iiyama, M., & Dobie, P. (2015). *From transition fuel to viable energy source: Improving sustainability in the sub-Saharan charcoal sector*. ICRAF Working Paper No. 196. Nairobi: World Agroforestry Centre. Retrieved from http://outputs.worldagroforestry.org/

Njenga, M., Iiyama, M., Jamnadass, R., Helander, H., Larsson, L., Leeuw, J. de,. . . Sundberg, C. (2016). Gasifier as a cleaner cooking system in rural Kenya. *Journal of Cleaner Production*, *121*, 208–217.

Njenga, M., Iiyama, M., Leeuw, J. de, Röing de Nowina, K., Kätterer, T., Kimutai, G., & Sundberg, C. (2015). Keeping healthy and saving trees: Cooking with a gasifier saves fuel and time, reduces smoke and produces charcoal for other uses. *MITI Magazine*, *April-June 2015*, 37–39. Retrieved from http://www.slu.se/bio-char-kenya

Nyambane, A., Njenga, M., Oballa, P., Mugo, P., Ochieng, C., Johnson, O.,. . . Iiyama. (2014). *Sustainable firewood access and utilization: Achieving cross-sectoral integration in Kenya*. Technical brief. Nairobi: World Agroforestry Centre and Stockholm Environment Institute. Retrieved from http://outputs.worldagroforestry.org/

Oballa, P. O., Konuche, P. K. A., Muchiri, M. N., & Kigomo, B. N. (2010). *Facts on growing and use of Eucalyptus in Kenya*. Nairobi: Kenya Forestry Research Institute. Retrieved from https://www.fornis.net/system/files/new%20eucalyptus%20final.pdf

Ostrom, E. (1999). Revisiting the commons: Local lessons, global challenges. *Science*, *284*(5412), 278–282. doi:10.1126/science.284.5412.278

Partnership for Clean Indoor Air. (2012). *Test results of cook stove performance*. Report prepared by the Aprovecho Research Center. Retrieved from http://www.pciaonline.org/files/Test-Results-Cookstove-Performance.pdf

Pennise, D. M., Smith, K. R., Kithinji, J. P., Rezende, M. E., Raad, T. J., Zhang, J., & Fan, C. (2001). Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. *Journal of Geophysical Research*, *106*(D20), 24143. doi:10.1029/2000JD000041

Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, *1*(4), 221–227. doi:10.1038/ngeo156

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science & Technology*, *44*(2), 827–833. doi:10.1021/es902266r

Roden, C. A., Bond, T. C., Conway, S., & Pinel, A. B. O. (2006). Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. *Environmental Science & Technology*, *40*(21), 6750–6757. doi:10.1021/es052080i

Roth, C. (2014). *Micro-gasification: cooking with gas from biomass: An introduction to concepts and applications of wood-gas burning technologies for cooking*. Poverty-oriented basic energy services (HERA) programme (2nd revised edition). Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Retrieved from https://cleancookstoves.org/binary-data/RESOURCE/file/000/000/286-1.pdf

Salami, A., Kamara, A. B., & Brixiova, Z. (2010). *Smallholder agriculture in east Africa: Trends, constraints and opportunities*. Working Paper Series No. 105. Tunis: African Development Bank Group. Retrieved from http://www.afdb.org/en/documents/publications/

Scholz, S. B., Sembres, T., Roberts, K., Whitman, T., Wilson, K., & Lehmann, J. (2014). *Biochar systems for smallholders in developing countries: Leveraging current knowledge and exploring future potential for climate-smart agriculture*. A World Bank study. Washington, D.C.: World Bank Group. Retrieved from http://documents.worldbank.org/

Sheng, C., & Azevedo, J. (2005). Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass and Bioenergy*, *28*(5), 499–507. doi:10.1016/j.biombioe.2004.11.008

Shindell, D. T., Faluvegi, G., Koch, D. M., Schmidt, G. A., Unger, N., & Bauer, S. E. (2009). Improved attribution of climate forcing to emissions. *Science (New York, N.Y.)*, *326*(5953), 716–718. doi:10.1126/science.1174760

Smith, K., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z.,. . . Rehfuess, E. (2014). Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annual Review of Public Health*, *35*, 185–206. doi:10.1146/annurev-publhealth-032013-182356

Smith, K., & Haigler, E. (2008). Co-benefits of climate mitigation and health protection in energy systems: Scoping methods. *Annual Review of Public Health*, *29*, 11–25. doi:10.1146/annurev.publhealth.29.020907.090759

Smith, K., Uma, R., Kishore, V., Zhang, J., Joshi, V., & Khalil, M. (2000b). Greenhouse implications of household stoves: An analysis for India. *Annual Review of Energy and the Environment*, *25*(1), 741–763. doi:10.1146/annurev.energy.25.1.741

Smith, K., Uma, R., Kishore, V. V. N., Lata, K., Joshi, V., Zhang, J.,. . . Khalil, M. A. K. (2000a). *Greenhouse gases from small-scale combustion devices in developing countries: Phase IIa – household stoves in India*. Report prepared for EPA, EPA-600/R-00-052. Washington, D.C.: Office of Research and Development, U.S. Environmental Protection Agency. Retrieved from http://nepis.epa.gov/Exe/ZyPDF.cgi/P1009BSZ.PDF?Dockey=P1009BSZ.PDF

Söderberg, C. (2013). *Effects of biochar amendment in soils from Kisumu, Kenya* (Bachelor thesis). Swedish University of Agricultural Sciences, Uppsala.

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). Chapter 2 – a review of biochar and its use and function in soil. *Advances in Agronomy, Academic Press*, *105*, 47–82. doi:10.1016/S0065-2113(10)05002-9

Sparrevik, M., Adam, C., Martinsen, V., Jubaedah, & Cornelissen, G. (2015). Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved “retort” kilns. *Biomass and Bioenergy*, *72*, 65–73. doi:10.1016/j.biombioe.2014.11.016

Sparrevik, M., Field, J. L., Martinsen, V., Breedveld, G. D., & Cornelissen, G. (2013). Life cycle assessment to evaluate the environmental impact of biochar implementation in conservation agriculture in Zambia. *Environmental Science & Technology*, *47*(3), 1206–1215. doi:10.1021/es302720k

Sparrevik, M., Lindhjem, H., Andria, V., Fet, A. M., & Cornelissen, G. (2014). Environmental and socioeconomic impacts of utilizing waste for biochar in rural areas in Indonesia – a systems perspective. *Environmental Science & Technology*, *48*(9), 4664–4671. doi:10.1021/es405190q

Stiebert, S. (2012). *National climate change action plan – mitigation: Chapter 2 – preliminary greenhouse gas inventory*. Nairobi: Government of Kenya. Retrieved from http://www.kccap.info/

Suh, S., & Huppes, G. (2005). Methods for Life Cycle Inventory of a product. *Journal of Cleaner Production*, *13*(7), 687–697. doi:10.1016/j.jclepro.2003.04.001

Torres, D. (2011). *Biochar production with cook stoves and use as a soil conditioner in Western Kenya* (Doctoral dissertation). Cornell University, Ithaca, N.Y.

Torres-Rojas, D., Lehmann, J., Hobbs, P., Joseph, S., & Neufeldt, H. (2011). Biomass availability, energy consumption and biochar production in rural households of Western Kenya. *Biomass and Bioenergy*, *35*(8), 3537–3546. doi:10.1016/j.biombioe.2011.05.002

Tryner, J., Willson, B. D., & Marchese, A. J. (2014). The effects of fuel type and stove design on emissions and efficiency of natural-draft semi-gasifier biomass cookstoves. *Energy for Sustainable Development*, *23*, 99–109. doi:10.1016/j.esd.2014.07.009

Turpin, B. J., & Lim, H.-J. (2001). Species contributions to PM2.5 mass concentrations: Revisiting common assumptions for estimating organic mass. *Aerosol Science and Technology*, *35*(1), 602–610. doi:10.1080/02786820119445

UN. (1987). *Energy statistics: Definitions, units of measure and conversion factors*. *Studies in methods Ser. F: Vol. 44*. New York: United Nations.

UN General Assembly. (2013). United Nations decade of sustainable energy for all. Report of the Secretary-General, A/68/309 (6 August 2013). Retrieved from www.undocs.org/A/68/309

UN General Assembly. (2015). Draft outcome document of the United Nations summit for the adoption of the post-2015 development agenda. Draft resolution submitted by the President of the General Assembly, A/69/L.85 (12 August 2015). Retrieved from www.undocs.org/A/69/L.85

UNEP. (2001). *An assessment of the status of the world's remaining closed forests*. Nairobi: Division of Early Warning and Assessment, United Nations Environment Programme. Retrieved from https://na.unep.net/siouxfalls/publications/closedforest.pdf

Verheijen, F., Jeffery, S., Bastos, A. C., van der Velde, M., & Diafas, I. (2010). *Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions*. *Scientific and technical research series: EUR 24099 EN*. Luxembourg: Office for the Official Publications of the European Communities.

VITA. (1985). *Testing the efficiency of wood-burning cookstoves: International standards*. Prepared by Volunteers in Technical Assistance based on a meeting of experts in December 1982. Retrieved from http://www.aprovecho.org/lab/images/stories/camp08/Testing.pdf

Whitman, T., Nicholson, C. F., Torres, D., & Lehmann, J. (2011). Climate change impact of biochar cook stoves in western Kenyan farm households: System dynamics model analysis. *Environmental Science & Technology*, *45*(8), 3687–3694. doi:10.1021/es103301k

Whitman, T., Scholz, S. M., & Lehmann, J. (2010). Biochar projects for mitigating climate change: An investigation of critical methodology issues for carbon accounting. *Carbon Management*, *1*(1), 89–107. doi:10.4155/cmt.10.4

WHO. (2014). *WHO guidelines for indoor air quality: Household fuel combustion*. Geneva: World Health Organization. Retrieved from http://gbv.eblib.com/patron/FullRecord.aspx?p=2076210

World Bank. (2015). *World development indicators*. Released in September 2015. Washington, D.C.: The World Bank Group. Retrieved from http://data.worldbank.org/data-catalog/world-development-indicators

WRI. (2007). *Nature's benefits in Kenya: An atlas of ecosystems and human well-being*. Washington, D.C. and Nairobi: World Resources Institute. Retrieved from http://www.wri.org/biodiv/pubs_description.cfm?pid=4279

WRI. (2015). *Climate analysis indicators tool: WRI’s climate data explorer*. Washington, D.C.: World Resources Institute. Retrieved from http://cait2.wri.org

# 9 Appendix

## 9.1 Appendix A: Socio-economic country profile of Kenya

**Table A1.** Kenya country profile; unless fully cited, all data retrieved from the World Bank's World Development Indicators database (World Bank, 2015)

| | | Year | Primary data source |
|---|---|---|---|
| **Population and welfare** | | | |
| Population [million people] | 44.9 | 2014 | UN |
| Population growth 2005-2014 [annual %] | 2.6 | 2005-2014 | UN; own calculation |
| GNI per capita, Atlas method [current US$] | 1,290 | 2014 | World Bank and OECD |
| Poverty headcount ratio at national poverty lines [% of population] | 45.9 | 2005 | World Bank |
| GINI index on inequality | 47.7 | 2005 | World Bank estimate |
| Rural population [% of total population] | 74.8 | 2014 | World Bank estimate |
| Rural population growth 2005-2014 [annual %] | 2.1 | 2005-2014 | World Bank estimate; own calculation |
| Rural poverty headcount ratio at national poverty lines [% of rural population] | 49.1 | 2005 | World Bank |
| Rural poverty gap at national poverty lines [%] | 17.5 | 2005 | World Bank |
| Urban population [% of total] | 25.2 | 2014 | World Bank estimate |
| Urban population growth 2005-2014 [annual %] | 4.3 | 2005-2014 | World Bank estimate; own calculation |
| Urban poverty headcount ratio at national poverty lines [% of urban population] | 33.7 | 2005 | World Bank |
| Urban poverty gap at national poverty lines [%] | 11.4 | 2005 | World Bank |
| **Resources and energy** | | | |
| Surface area [1,000 ha] | 58,037 | 2014 | FAO |
| Land area [1,000 ha] | 56,914 | 2015 | FAO, 2015, p. 5 |
| Forest area [1,000 ha] | 4,413 | 2015 | FAO, 2015, p. 5 |
| Forest area [% of land area] | 7.8 | 2015 | FAO, 2015, p. 5 |
| Other wooded area [1,000 ha] | 9,365 | 2015 | FAO, 2015, p. 5 |
| Other wooded area [% of land area] | 16.5 | 2015 | FAO, 2015, p. 5 |
| Forest area loss 2005-2012 [annual 1,000 ha] | 11 | 2005-2012 | FAO; own calculation |
| Closed forest area [1,000 ha] | 980 | 2001 | UNEP, 2001, p. 41 |
| Closed forest area [% of land area] | 1.7 | 2001 | UNEP, 2001, p. 41 |
| Forest area loss [annual 1,000 ha] | 5 | 2009 | NEMA, 2009, p. 9 |
| Agricultural land [1,000 ha] | 27,430 | 2012 | FAO |
| Agricultural land [% of land area] | 48.2 | 2012 | FAO |
| Cultivable land [% of land area] = arable land + permanent cropland | 10.8 | 2012 | FAO; own calculation |

| | | | |
|---|---|---|---|
| Renewable energy consumption [% of total final energy consumption] | 78.5 | 2012 | World Bank |
| Access to electricity [% of population] | 23.0 | 2012 | World Bank |
| Access to electricity, rural [% of rural population] | 6.7 | 2012 | World Bank |
| Access to electricity, urban [% of urban population] | 58.2 | 2012 | World Bank |
| Access to non-solid fuel [% of population] | 16.2 | 2012 | World Bank |
| Access to non-solid fuel, rural [% of rural population] | 2.6 | 2012 | World Bank |
| Access to non-solid fuel, urban [% of urban population] | 58.2 | 2012 | World Bank |
| | | | |
| **Economy and agriculture** | | | |
| GDP growth 2005-2014 [annual %] | 5.3 | 2005-2014 | World Bank; own calculation |
| Agricultural GDP growth 2005-2014 [annual %] | 3.1 | 2005-2014 | World Bank; own calculation |
| Agriculture, value added [% of GDP] | 30.3 | 2014 | World Bank |
| Industry, value added [% of GDP] | 19.4 | 2014 | World Bank |
| Services, etc., value added [% of GDP] | 50.4 | 2014 | World Bank |
| Employment in agriculture [% of total employment] | 61.1 | 2005 | ILO |
| Contribution of smallholders to production [% of total agricultural output] | 75.0 | 2009 | AfDB/FAO cited in AfDB, 2010, p. 12 |
| Average size of holding [acre per household] | 2.5 | 2005/06 | KNBS, 2006, p. 193 |
| Cereal yield [kg per ha] | 1727.1 | 2013 | FAO |
| Parcels under irrigation [%] | 6.0 | 2005/06 | KNBS, 2006, p. 198 |
| Cultivated area equipped for irrigation [% of cultivated area] | 2.34 | 2010 | FAO, 2015 |
| Parcels using fertiliser [%] | 69.4 | 2005/06 | KNBS, 2006, p. 198 |
| Parcels using inorganic fertiliser [%] | 52.1 | 2005/06 | KNBS, 2006, p. 198 |
| Parcels using organic fertiliser [%] | 37.4 | 2005/06 | KNBS, 2006, p. 198 |
| Fertilizer consumption [kg per ha of arable land] | 44.3 | 2012 | FAO |
| | | | |
| **Emissions** | | | |
| $CO_2$ emissions [metric tons per capita] | 0.3 | 2011 | CDIAC |
| $CO_2$ emissions from solid fuel consumption [% of total] | 7.4 | 2011 | CDIAC |
| Agricultural methane emissions [% of total] | 53.9 | 2010 | EC JRC |
| Agricultural nitrous oxide emissions [% of total] | 86.9 | 2010 | EC JRC |
| $PM_{2.5}$ air pollution, mean annual exposure [micrograms per cubic meter] | 11.4 | 2013 | Brauer, M. et al. |
| $PM_{2.5}$ air pollution, population exposed to levels above WHO guidelines [% of total] | 59.8 | 2013 | Brauer, M. et al. |
| | | | |
| **Embu district** | | | |
| Total population | 296,992 | 2009 | KNBS, 2010, p. 25 |
| Rural population [% of total population] | 73% | 2009 | KNBS, 2010, pp. 25-28; own calculation |

| | | | |
|---|---|---|---|
| Households | 80,138 | 2009 | KNBS, 2010, p. 25 |
| Land area [km²] | 725.50 | 2009 | KNBS, 2010, p. 25 |
| Rural population | 216,782 | 2009 | KNBS, 2010, p. 28 |
| Households | 56,173 | 2009 | KNBS, 2010, p. 28 |
| Average household size | 3.9 | 2009 | KNBS, 2010, p. 28; own calculation |
| Land area [km²] | 630.10 | 2009 | KNBS, 2010, p. 28 |
| Parcels under irrigation [%] | 5.0 | 2005/06 | KNBS, 2006, p. 198 |
| Parcels using fertiliser [%] | 92.8 | 2005/06 | KNBS, 2006, p. 198 |
| Parcels using inorganic fertiliser [%] | 89.9 | 2005/06 | KNBS, 2006, p. 198 |
| Parcels using organic fertiliser [%] | 55.5 | 2005/06 | KNBS, 2006, p. 198 |

## 9.2 Appendix B: Energy sources and consumption

**Table A2.** Kenya's total gross energy consumption by sector and fuel type, year 2000 (own calculation based on MoE, 2002, p. 31)

| Sector | | Subtotal biomass | Biomass | | | | | | Modern energy | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Firewood | Wood for charcoal | Industrial wood | Wood wastes | Farm residues | Charcoal | Petroleum | Electricity | |
| Rural households | Absolute consumption [1,000 GJ] | 386,057 | 225,040 | 121,999 | 0 | 2,183 | 36,835 | | 6,819 | 336 | 393,212 |
| | Biomass consumption [tonnes] | 24,476,379 | 14,065,004 | 7,624,935 | 0 | 136,459 | 2,649,981 | 1,829,984 | | | |
| | Share of national consumption | 55.7% | 32.5% | 17.6% | 0.0% | 0.3% | 5.3% | | 1.0% | 0.0% | 57% |
| | Share of rural hh consumption | 98.2% | 57.2% | 31.0% | 0.0% | 0.6% | 9.4% | | 1.7% | 0.1% | 100% |
| Urban households | Absolute consumption [1,000 GJ] | 103,590 | 5,739 | 96,331 | 0 | 1,342 | 178 | | 6,656 | 2,603 | 112,849 |
| | Biomass consumption [tonnes] | 6,476,067 | 358,709 | 6,020,663 | 0 | 83,863 | 12,832 | 1,444,959 | | | |
| | Share of national consumption | 15.0% | 0.8% | 13.9% | 0.0% | 0.2% | 0.0% | | 1.0% | 0.4% | 16% |
| | Share of urban hh consumption | 91.8% | 5.1% | 85.4% | 0.0% | 1.2% | 0.2% | | 5.9% | 2.3% | 100% |
| Total household consumption | Absolute consumption [1,000 GJ] | 489,647 | 230,779 | 218,330 | 0 | 3,525 | 37,013 | | 13,475 | 2,939 | 506,061 |
| | Biomass consumption [tonnes] | 30,952,446 | 14,423,713 | 13,645,598 | 0 | 220,322 | 2,662,813 | 3,274,944 | | | |
| | Share of national consumption | 70.7% | 33.3% | 31.5% | 0.0% | 0.5% | 5.3% | | 1.9% | 0.4% | 73% |
| | Share of hh consumption | 96.8% | 45.6% | 43.1% | 0.0% | 0.7% | 7.3% | | 2.7% | 0.6% | 100% |
| Other | Absolute consumption [1,000 GJ] | 68,421 | 20,900 | 45,774 | 1,747 | 0 | 0 | | 111,485 | 6,895 | 186,801 |
| | Biomass consumption [tonnes] | 3,437,233 | 467,145 | 2,860,900 | 109,188 | 0 | 0 | 686,616 | | | |
| | Share of national consumption | 9.9% | 3.0% | 6.6% | 0.3% | 0.0% | 0.0% | | 16.1% | 1.0% | 27% |
| | Share of other consumption | 36.6% | 11.2% | 24.5% | 0.9% | 0.0% | 0.0% | | 59.7% | 3.7% | 100% |
| Total national consumption | Absolute consumption [1,000 GJ] | 558,068 | 251,679 | 264,104 | 1,747 | 3,525 | 37,013 | | 124,960 | 9,834 | 692,862 |
| | Share of national consumption | 80.5% | 36.3% | 38.1% | 0.3% | 0.5% | 5.3% | | 18.0% | 1.4% | 100% |

**Table A3.** Percentage distribution of households by main source of cooking fuel and region (adapted from KNBS, 2005, p. 248)

| Region | Households | Subtotal biomass [%] | Traditional biomass [%] | | | Modern energy [%] | | | Other [%] |
|---|---|---|---|---|---|---|---|---|---|
| | | | Firewood | Wood for charcoal | Biomass residue | Petroleum | Gas | Electricity | |
| Kenya | 6,866,374 | 81.9 | 68.3 | 13.3 | 0.3 | 13.2 | 3.5 | 0.6 | 0.7 |
| Rural | 5,151,105 | 95.8 | 87.7 | 7.7 | 0.4 | 2.7 | 0.7 | 0.2 | 0.5 |
| Urban | 1,715,269 | 40.3 | 10.0 | 30.2 | 0.1 | 44.6 | 12.0 | 1.8 | 1.3 |
| Embu district | 75,976 | 92.5 | 82.5 | 9.8 | 0.2 | 6.6 | 0.8 | 0.2 | - |

**Table A4.** Annually accessible sustainable wood yield per vegetation type, year 2000 (adapted from MoE, 2002, p.41)

| Vegetation type | Kenya total | | Eastern province | |
|---|---|---|---|---|
| | Biomass supply [m³/yr] | Share | Biomass supply [m³/yr] | Share |
| Closed forest | 78,143 | 0.4% | 8,270 | 0.2% |
| Woodland | 409,022 | 2.2% | 71,671 | 1.6% |
| Bush land | 3,196,141 | 17.4% | 541,852 | 11.8% |
| Wooded grassland | 79,135 | 0.4% | 154,650 | 3.4% |
| Grassland | 8,979 | 0.05% | 3,340 | 0.1% |
| Farmland | 12,942,856 | 70.4% | 3,732,953 | 81.1% |
| Plantations | 951,290 | 5.2% | 92,679 | 2.0% |
| Sub-total [m³] | 18,377,780 | 100.0% | 4,605,419 | 100.0% |

## 9.3 Appendix C: Countrywide GHG emissions

**Table A5.** Kenya's countrywide GHG emissions; all data retrieved from the World Resources Institute's Climate Data Explorer (WRI, 2015); primary sources: $CO_2$ emissions from fuel combustion data (IEA, 2013); Land-use change and forestry, or agriculture indicators (FAO, 2015)

**GHG emissions totals and by gas, year 2012, absolute values [$MtCO_2e$]**

| Country | GHG total | GHG total | $CO_2$ | $CH_4$ | $N_2O$ | F-gases |
|---|---|---|---|---|---|---|
| Calculation | excl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry |
| World | 44815.54 | 47598.55 | 36421.81 | 7298.60 | 3105.04 | 773.11 |
| Kenya | 59.48 | 69.60 | 20.56 | 30.09 | 18.72 | 0.23 |
| Kenya's share | 0.13% | 0.15% | 0.06% | 0.41% | 0.60% | 0.03% |

**GHG emissions totals and by gas, year 2012, relative values [$tCO_2e$ per capita]**

| Country | GHG total | GHG total | $CO_2$ | $CH_4$ | $N_2O$ | F-gases |
|---|---|---|---|---|---|---|
| Calculation | excl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry | incl. LUC and forestry |
| World | 6.36 | 6.76 | 5.17 | 1.04 | 0.44 | 0.11 |
| Kenya | 1.38 | 1.61 | 0.48 | 0.70 | 0.43 | 0.01 |
| Kenya's share | 22% | 24% | 9% | 67% | 98% | 5% |

**Kenya's GHG emissions by sector, year 2012 [$MtCO_2e$]**

| | Agriculture | Energy | LUC and forestry | Industrial processes | Bunker fuels | Waste | Total |
|---|---|---|---|---|---|---|---|
| Absolute | 40.81 | 17.60 | 10.12 | 2.19 | 2.16 | 0.84 | 73.72 |
| Share of sector | 55% | 24% | 14% | 3% | 3% | 1% | 100% |

**Kenya's GHG emissions by energy sub-sector, year 2012 [$MtCO_2e$]**

| | Other fuel combustion | Transportation | Manufacturing and construction | Electricity and heat | Fugitive emissions | Total |
|---|---|---|---|---|---|---|
| Absolute | 8.07 | 4.78 | 2.72 | 1.99 | 0.04 | 17.60 |
| Share of sub-sector | 46% | 27% | 15% | 11% | 0.2% | 100% |

## 9.4 Appendix D: Life cycle inventory data

**Table A6.** Characteristics of the available primary and secondary fuels (own calculations based on Gulyurtlu, Penha, & Cabrita, 1997; Njenga et al., 2016; Pennise et al., 2001; UN, 1987, p. 32)

| **Primary fuels** | | | | |
|---|---|---|---|---|
| Fuel type | **On-farm firewood** | | **Off-farm firewood** | **Crop residues** |
| Resource base | Prunings from *Grevillea robusta* | Prunings from Eucalyptus and coffee shrubs | Twigs and marginal wood from trees and shrubs, mix of tropical wood species | Maize cobs |
| Sourcing | On-farm collection, market | On-farm collection, market | Off-farm collection, market | On-farm collection |
| Use | Three-stone stove, TLUD | Three-stone stove, TLUD | Three-stone stove, TLUD | TLUD |
| Moisture d.b. [%] | 10.7% | 10.7% | 10.7% | 9.9% |
| Carbon d.b. [%] | 68.0% | 45.6% | 42.0% | 47.0% |
| Ash d.b. [%] | 5.5% | 1.4% | 1.0% | 4.2% |
| LHV w.b. [MJ/kg] | 17.7 | 15.3 | 16.7 | 17.2 |
| LHV d.b. [MJ/kg] | 19.6 | 16.9 | 18.5 | 18.9 |

| **Secondary fuels** | | | | | |
|---|---|---|---|---|---|
| Fuel type | **Conventional charcoal** | **TLUD wood charcoal** | | | **TLUD maize cob charcoal** |
| Conversion | Earth mound kiln | TLUD gasifier | TLUD gasifier | TLUD gasifier | TLUD gasifier |
| Resource base | Market mix of Eucalyptus and Acaia wood at 22% Md | Prunings from *Grevillea robusta* at 10.7% Md | Prunings from Eucalyptus and coffee shrubs at 10.7% Md | Off-farm wood, mix of tropical wood species at 10.7% Md | Maize cobs at 9.9% Md |
| Sourcing | Market | On-farm production | On-farm production | On-farm production | On-farm production |
| Use | Kenya Ceramic Jiko | Kenya Ceramic Jiko | Kenya Ceramic Jiko | Kenya Ceramic Jiko | Kenya Ceramic Jiko |
| Moisture d.b. [%] | 5.3% | 7.2% | 7.2% | 7.2% | 8.7% |
| Carbon d.b. [%] | 78.7% | 75.7% | 75.7% | 75.7% | 82.8% |
| Ash d.b. [%] | 2.4% | 5.9% | 3.1% | 2.2% | 5.8% |
| LHV w.b. [MJ/kg] | 30.8 | 24.7 | 25.3 | 29.9 | 26.4 |
| LHV d.b. [MJ/kg] | 32.4 | 26.5 | 27.1 | 32.0 | 28.7 |

**Table A7.** Performance and emission factors of stove-fuel combinations for combustion; dry refers to bone-dry material, converted to 0% moisture content from the wet fuel; wet refers to the material as received, including the given moisture content; emission factors are rounded to 4 significant digits (own calculations based on Bailis et al., 2003; Bond et al., 2004; Drigo et al., 2015, p. 26; Jain, 1999; Roden et al., 2006; Smith et al., 2000a, pp. 32–70; Torres, 2011; Whitman et al., 2010)

| **Stove-fuel combinations for combustion** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Stove | **Three-stone stove** | | | **Kenya Ceramic Jiko** | | | | |
| Fuel type | On-farm firewood | On-farm firewood | Off-farm firewood | Conventional charcoal | TLUD wood charcoal | TLUD wood charcoal | TLUD wood charcoal | TLUD maize cob charcoal |
| Reference species | Eucalyptus | *Grevillea robusta* | Acacia | Charred Eucalyptus and Acacia | Charred *Grevillea robusta* | Charred Eucalyptus | Charred Acacia | Charred maize cobs |
| Thermal efficiency [%] | 15% | 15% | 15% | 30% | 40% | 40% | 30% | 32% |
| Carbon balance base | g/kg dry wood | g/kg dry wood | g/kg dry wood | g/kg dry charcoal | g/kg dry charcoal | g/kg dry charcoal | g/kg dry charcoal | g/kg dry charcoal |
| Fuel carbon in [g C/kg] | 456 | 680 | 420 | 750 | 757 | 757 | 757 | 828 |
| Solid carbon out [g C/kg] | 1.2 | 1.8 | 1.5 | 0 | 0 | 0 | 0 | 0 |
| Carbon emitted [g C/kg] | 455 | 678 | 419 | 750 | 757 | 757 | 757 | 828 |
| $CO_2$ [g pollutant/kg] | 1,536 | 2,290 | 1,390 | 2,400 | 2,423 | 2,423 | 2,423 | 2,341 |
| $CH_4$ [g pollutant/kg] | 2.833 | 4.225 | 3.200 | 18.95 | 19.13 | 19.13 | 19.13 | 18.48 |
| $N_2O$ [g pollutant/kg] | 0.0728 | 0.0728 | 0.1782 | 0.2537 | 0.2531 | 0.2531 | 0.2531 | 0.2531 |
| CO [g pollutant/kg] | 60.15 | 89.70 | 79.00 | 273.7 | 276.3 | 276.3 | 276.3 | 400.4 |
| NMHCs [g pollutant/kg] | 7.982 | 11.90 | 1.600 | 3.368 | 3.401 | 3.401 | 3.401 | 3.286 |
| BC [g C/kg] | 0.2825 | 0.4212 | 0.3300 | 0.1831 | 0.1848 | 0.1848 | 0.1848 | 0.3571 |
| OC [g C/kg] | 0.6591 | 0.9829 | 0.7700 | 0.2380 | 0.2403 | 0.2403 | 0.2403 | 0.4643 |
| $SO_2$ [g pollutant/kg] | 0.3996 | 0.3996 | 0.1998 | 1.2619 | 1.4800 | 1.7564 | 0.9458 | 1.6478 |
| RB credit [g $CO_2$/kg] | 1,666 | 2,485 | 869 | 2,521 | 2,774 | 2,774 | 1,573 | 3,034 |
| Biochar credit [g $CO_2$/kg] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table A8.** Performance and emission factors of stove-fuel combinations for conversion, biodegradation of unused residues and biochar application to soil; dry refers to bone-dry material, converted to 0% moisture content from the wet fuel; wet refers to the material as received, including the given moisture content; emission factors are rounded to 4 significant digits; higher credits refer to *Grevillea robusta* and Eucalyptus, lower credits to Acacia (own calculations based on Bond et al., 2004; Drigo et al., 2015, p. 26; Gulyurtlu et al., 1997; Jain, 1999; MacCarty et al., 2008; Pennise et al., 2001; Smith et al., 2000a, p. 70; Torres, 2011; UN, 1987, p. 32; Whitman et al., 2010)

| Stove-fuel combinations for conversion | | | | | | Others | | |
|---|---|---|---|---|---|---|---|---|
| Stove | **Earth mound kiln** | **TLUD gasifier** | | | | **Biodegradation** | **Biochar to soil** | |
| Fuel type | Firewood | On-farm firewood | On-farm firewood | Off-farm firewood | Maize cobs | Crop residues | TLUD wood charcoal | TLUD maize cob charcoal |
| Reference species | Eucalyptus and Acacia | *Grevillea robusta* | Eucalyptus | Acacia | Maize cobs | Maize cobs | Charred Grev., Eucal. and Acacia | Charred maize cobs |
| Thermal efficiency [%] | 0% | 21% | 21% | 21% | 19% | 0% | 0% | 0% |
| Conversion efficiency [%] | 47.3% | 29.2% | 29.2% | 29.2% | 29.5% | 0% | 0% | 0% |
| Char yield [% dry mass] | 27.5% | 21.6% | 18.2% | 16.9% | 19.4% | 0% | 0% | 0% |
| Carbon yield [% carbon] | 46.9% | 24.0% | 30.1% | 30.2% | 33.9% | 0% | 0% | 0% |
| Carbon balance base | g/kg dry charcoal | g/kg dry wood | g/kg dry wood | g/kg dry wood | g/kg dry cobs | g/kg dry cobs | g/kg dry charcoal | g/kg dry cobs |
| Fuel carbon in [g C/kg] | 1600 | 680 | 456 | 420 | 453 | 453 | 757 | 828 |
| Solid carbon out [g C/kg] | 750 | 163 | 137 | 127 | 160 | 0 | 0 | 0 |
| Carbon emitted [g C/kg] | 716 | 517 | 319 | 293 | 293 | 453 | 151 | 165 |
| $CO_2$ [g pollutant/kg] | 1,897 | 1,775 | 1,095 | 1,006 | 985.3 | 1,660 | 554.8 | 606.8 |
| $CH_4$ [g pollutant/kg] | 46.99 | 2.653 | 1.637 | 1.503 | 1.473 | 0 | 0 | 0 |
| $N_2O$ [g pollutant/kg] | 0.1541 | 0.0401 | 0.0401 | 0.0401 | 0.1203 | 0 | 0 | 0 |
| CO [g pollutant/kg] | 235.4 | 48.61 | 30.00 | 27.55 | 40.48 | 0 | 0 | 0 |
| NMHCs [g pollutant/kg] | 97.49 | 11.14 | 6.872 | 6.312 | 6.182 | 0 | 0 | 0 |
| BC [g C/kg] | 2.400 | 0.0974 | 0.0601 | 0.0552 | 0.1082 | 0 | 0 | 0 |
| OC [g C/kg] | 15.60 | 0.5708 | 0.3522 | 0.3235 | 0.6337 | 0 | 0 | 0 |
| $SO_2$ [g pollutant/kg] | 0.3155 | 0.0799 | 0.0799 | 0.0400 | 0.2797 | 0 | 0 | 0 |
| RB credit [g $CO_2$/kg] | 2,407 | 1,894 | 1,169 | 608.7 | 1,074 | 1,660 | 355.8 / 314.6 | 606.8 |
| Biochar credit [g $CO_2$/kg] | 0 | 0 | 0 | 0 | 0 | 0 | 2219 / 1258 | 2,427 |

## 9.5 Appendix E: Characterisation factors

**Table A9.** Characterisation factors for set 1 NRB (Kyoto gases only, emissions from non-renewable biomass), and set 2 (own compilation based on Bond et al., 2013; Bond, Zarzycki, Flanner, & Koch, 2011; Fuglestvedt et al., 2010; IPCC, 2013, pp. 714–740; Shindell et al., 2009)

| Pollutant | Pollutant group | $GWP_{100}$ | $GWP_{20}$ |
|---|---|---|---|
| $CO_2$ | Kyoto gases | 1 | 1 |
| $CH_4$ | Kyoto gases | 36 | 87 |
| $N_2O$ | Kyoto gases | 298 | 268 |
| CO | Ozone precursors | 4.98 | 18.6 |
| NMHCs | Ozone precursors | 4.23 | 14 |
| BC | Aerosols and precursors | 846 | 3200 |
| OC | Aerosols and precursors | -43.24 | -160 |
| $SO_2$ | Aerosols and precursors | -71.44 | -140 |
| RB-credit | Carbon credits | -1 | -1 |
| Biochar credit | Carbon credits | 0 | 0 |

**Table A10.** Characterisation factors for set 1 RB (Kyoto gases only, emissions from renewable biomass), and the carbon credit from biochar (own compilation based on IPCC, 2013, pp. 714–731)

| Pollutant | Pollutant group | $GWP_{100}$ | $GWP_{20}$ |
|---|---|---|---|
| $CO_2$ | Kyoto gases | 0 | 0 |
| $CH_4$ | Kyoto gases | 34 | 86 |
| $N_2O$ | Kyoto gases | 298 | 268 |
| Biochar credit | Carbon credits | -1 | -1 |

## 9.6 Appendix F: Farm model and sustainable development

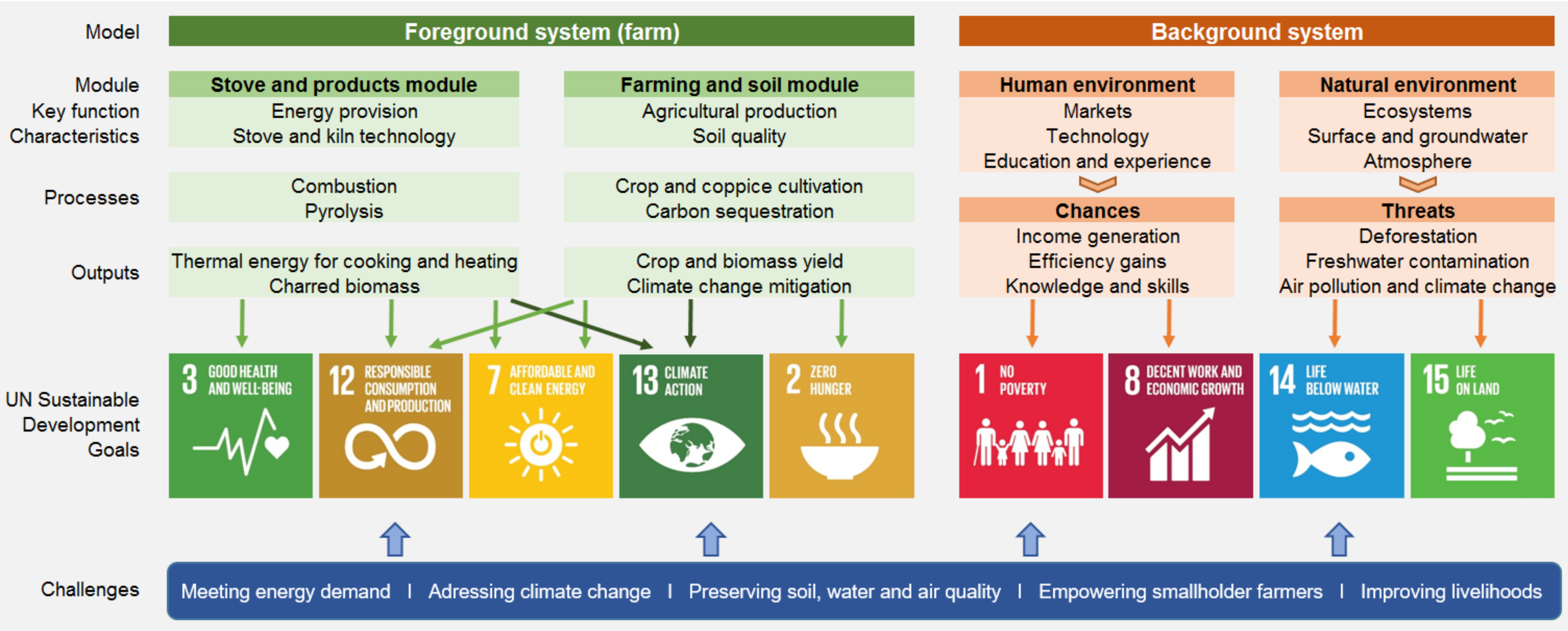


**Figure A1.** Links between the case study as implemented in the model and the UN Sustainable Development Goals