CARBONIZING URBAN BIOWASTE FOR LOW-COST CHAR PRODUCTION IN DEVELOPING COUNTRIES

A Review of Knowledge, Practices and Technologies

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Executive summary

Solid waste in the cities of low- and middle-income countries is characterized by a high organic fraction and management of this municipal solid waste is known for low collection and recycling rates, and inadequate disposal methods. Most of these countries also face the major challenge of supplying an affordable, reliable and sustainable cooking fuel to urban households. The majority of city residents use wood-based charcoal and the number of charcoal users is expected to rise over the years with increasing urbanization.

Wood-based charcoal has several advantages compared to other cooking fuels, including continuous availability in local markets (even in small quantities), ease of storage, higher heating value, lightweight, cleaner burning compared to wood, cheap stoves, and in many countries it is sold at lower price compared to liquefied petroleum gas (LPG) and electricity. However, wood-based charcoal is derived from a predominately informally organized supply chain, which is linked to unsustainable forest logging, low efficiency production methods and long transportation routes, which are all factors that contribute to environmental degradation. Since improving the sustainability of charcoal production is considered the most effective and realistic measure to enhance the sustainability of household cooking, several developing countries have started to initiate biomass energy strategies, which include efforts to promote access to appropriate, alternative sources of bioenergy.

The current state of the environment in cities of developing countries and their increasing charcoal demand raise the question if organic solid waste could be a suitable feedstock for low-cost char production. The char generated through slow pyrolysis of organic solid waste could be further processed into charcoal briquettes, a product of economic value with stable market demand and advantageous distribution properties. Use of municipal biowaste could stimulate their collection and, thereby, diminish the amount destined for disposal at dump sites. This approach could lead to reduced emissions linked to the uncontrolled decomposition of inappropriately disposed waste and reduced waste transportation, as well as the partial substitution of an unsustainably produced cooking fuel (wood-derived charcoal) without causing significant changes in traditional cooking appliances and behaviour.

This report reviews existing knowledge on char-making to help stakeholders understand under which circumstances carbonization of municipal biowaste may be feasible. The report starts with a general overview of common municipal solid waste management challenges in low-and middle-income countries. It then summarizes the current situation regarding conventional charcoal production and consumption as cooking fuel, reviewing some of the trends and theories behind the concept of 'household fuel switching'. It also describes biomass carbonization in details, i.e., input requirements, chemical conversion processes and output properties, and reviews information on existing biomass-to-char technologies: e.g., process and reactor types, capacity, construction materials, conversion efficiency, energy source, residence time, emissions, fixed carbon yield, auxiliary requirements, working life and capital cost. This part of the report draws heavily from literature on wood pyrolysis because there is limited information on slow pyrolysis of biowaste. The last chapter draws an analysis of the feasibility of biowaste carbonization in cities of developing countries and highlights challenges, opportunities and areas for further research.

This review concludes that the high demand for carbonized fuel in cities of low-and middle-income countries has created the market for waste-derived char briquettes. Yet, a major challenge to their production is having continuous access to dry, unmixed, homogeneous, uncontaminated substrates, which are available at no or low costs. In other words, a good supply of source-separated wastes that can be obtained near the point of their production is needed. Furthermore, most existing carbonization systems are either inefficient and polluting or relatively expensive. For a sustainable and financially viable waste-to-char business an appropriate, locally manufactured and operated, cost-effective system is required, which is non-polluting and energy-efficient with controlled use of all combustible by-products and waste heat.

On the policy level, there is a need to address the broader regulatory and tax framework in the charcoal sector. The current cost of charcoal in most developing countries does not reflect its true value because of lack of clear policies and enforcements, hence efforts to promote sustainably produced alternative cooking fuels will always be undercut by illegal charcoal, which is unregulated, bypasses many costs and reaches consumers at lower price at the expense of diminishing forests, adverse consequences on the environment and lost governments revenue.

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Abbreviations

ARTI	Appropriate Rural Technology Institute
BEST	Biomass Energy Strategies
CBA	Cost-Benefit Analysis
EGR	Exhaust Gas Recovery
FAO	Food and Agriculture Organization
FC	Fixed Carbon
GHG	Greenhouse Gases
HHV	Higher Heating Value
HTC	Hydrothermal Carbonization
IEA	International Energy Agency
ICPS	Improved Charcoal Production System
LAMIC	Low-and Middle-Income Country
LCA	Life Cycle Assessment
LEL	Limiting Explosion Limit
LFL	Limiting Flammability Limit
LHV	Lower Heating Value
LOC	Limiting Oxygen Concentration
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
NMHC	Non-Methane Hydrocarbons
PAH	Polycyclic Aromatic Hydrocarbons
PIC	Products of Incomplete Combustion
SSA	Sub-Saharan Africa
SWM	Solid Waste Management
TLUD	Top-Lit Up-Draft
TSP	Total Suspended Particulates
TZS	Tanzanian Shilling
VOC	Volatile Organic Compounds

1 Introduction

Cities in low- and middle-income countries (LAMICs) are facing immense challenges due to rapid population and urbanization growth. Among many issues, the following two are particularly striking: the challenge of providing adequate and equitable solid waste management (SWM) services, which in most LAMICs are characterized by waste with a high fraction of organic matter, low collection rates and inadequate disposal methods (e.g., Scheinberg et al., 2010; Guerrero et al., 2012; Hoornweg and Bhada-Tata, 2012; Zurbrügg, 2013) and supplying an affordable, reliable and sustainable cooking fuel to urban households. Despite major efforts during the past decade, charcoal still remains the primary source of cooking fuel for the vast majority of urban citizens in LAMICs, and the predominately informally organized charcoal supply chain is associated with unsustainable forest logging, low efficiency production methods, long transportation routes and end use in inefficient stoves (e.g., IEA, 2010; Maes and Verbist, 2012; Owen et al., 2013). It is widely acknowledged that the effects of both urban challenges pose considerable risks to environmental and human health (SWM: Cointreau, 2006; Manga, 2007; Scheinberg et al., 2010; Zurbrügg, 2013; Charcoal: GTZ, 2008; Chidumayo and Gumbo, 2013; Zulu and Richardson, 2013).

The thermochemical method of carbonization, a low-temperature slow pyrolysis process, presents one possible option for biowaste-to-cooking-fuel conversion, which can partly address this situation and is already widely practiced for the utilization of agricultural residues. This report explores the technical potential of valorising certain urban organic waste streams into char, which can be further processed to charcoal briquettes, a product of economic value for which there is stable market demand and advantageous distribution properties. This could stimulate the collection rate of biowaste in cities of LAMICs and diminish the amount destined for disposal at dump sites. This approach would lead to reduced emissions linked to the uncontrolled decomposition of inappropriately disposed waste and reduced waste transportation, as well as the partial substitution of an unsustainably produced cooking fuel (wood-derived charcoal) without requiring significant changes in current cooking appliances and behaviour.

This report reviews the challenges in SWM and charcoal in chapter 2 and chapter 3 respectively, and then in chapter 4 it presents detailed information about the decentralized carbonization of biowaste for char production (structured along its value chain, i.e., input requirements, conversion process, existing technologies and output properties). As literature on wood carbonization compared to biowaste carbonization is abundant and the fundamental conversion processes are similar, this section draws heavily from sources discussing wood pyrolysis. The focus of this report is *slow* pyrolysis and only those technologies used for source-separated biomass/wastes are presented. More information on pyrolysis for the mixed fraction of municipal solid waste (MSW) can be found elsewhere (e.g., Chen et al., 2014). Chapter 5 investigates the feasibility of slow pyrolysis treatment for biowaste in LAMICs by presenting challenges, opportunities and areas for further research.

2 Solid waste management in cities of developing countries

The municipal SWM system comprises generation, storage, collection, transfer and transport, and processing and disposal of solid wastes coming from residential, commercial or institutional sources. Proper municipal SWM aims at protecting human health, preventing environmental degradation and recovering valuable resources and is referred to as one of the key challenges of the 21st century (Hoornweg and Bhada-Tata, 2012; UN Department of Social and Economic Affairs, 2012; Scheinberg et al., 2010; Wilson, 2007; Henry et al., 2006; Nemerow, 2009). The provision of equitable and reliable SWM remains particularly difficult in LAMICs (Guerrero et al., 2012; Marshall and Farahbakhsh, 2013; Wilson et al., 2013). Reasons for the exacerbated problems in LAMICs include rapid urbanization, demographic changes, unregulated growth of settlements and topographically challenging situations on the one hand, and a lack of effective organizational structure, financial resources, viable business models, endorsement by government and compliance with legislation on the other hand (Zurbrügg, 2013). Deficient SWM negatively affects human health, as well as local and global environmental conditions, and social and economic development (Cointreau, 2006; Manga, 2007; Bogner et al., 2008; Bleck and Wettberg, 2012).
A widely accepted analytical framework for SWM, particularly used in LAMICs, is the concept of Integrated Sustainable Waste Management (ISWM). It distinguishes three principal dimensions of SWM: the physical system components (infrastructure), the stakeholders (human interaction) and the sustainability aspects (enabling environment, including technical, environmental, financial, economic, social, institutional and political aspects) (Schübeler et al., 1996; Van de Klundert and Anschütz, 2001; Scheinberg et al., 2010; Wilson et al., 2013), all of which need to be addressed in order for a SWM system to work sustainably over the long term.

2.1 Waste generation and composition

Waste generation expands with increases in population, economic development, income levels, and urbanization, as well as changes in lifestyle preferences and consumption (Seadon, 2006). The correlation between gross national income (GNI) and generated municipal solid waste has been shown by Cointreau (1983) and confirmed by many studies (e.g., Rouse et al., 2008; Sandec/Eawag, 2008; Scheinberg et al., 2010; Wilson et al., 2012). According to Hoornweg and Bhada-Tata (2012), urban residents produce about twice as much waste as their rural counterparts. Table 1 shows the current and projected MSW generation in LAMICs and high income countries where LAMICs generates about half of the MSW compared to high income countries. Furthermore, MSW generation is expected to double by 2025, mostly due to increases in population.

Table 1: Current waste generation by income class and projections for 2025
(adapted from Hoornweg and Bhada-Tata, 2012)

	Current available data			Projections for 2025			
Income level	**Total urban population** (millions)	**Urban waste generation** Per capita (kg/cap/day)	Total (tons/day)	**Projected population** Total pop. (millions)	Urban pop. (millions)	**Projected urban waste** Per capita (kg/cap/day)	Total (tons/day)
Low income	393	0.60	204.802	1.637	676	0.86	584.272
Middle income	1.865	0.90	1.677.907	4.898	2.699	1.37	3.705.843
High income	774	2.13	1.649.547	1.112	912	2.1	1.879.590
Total	*2.982*	*1.19*	*3.532.256*	*7.647*	*4.287*	*1.4*	*6.069.705*

Waste composition is influenced by diverse factors, such as the level of economic development, cultural norms, geographical location, energy sources, and climate (Hoornweg and Bhada-Tata, 2012). Thus, not only do waste quantities differ significantly between developing and high-income countries, but there are also substantial differences in terms of composition (Coffey and Coad, 2010). One of the main characteristics of MSW in LAMICs is the high share of organic waste (also named biowaste), which often comprises more than 50% to the total waste generated, and can be as high as 85% (Zurbrügg, 2002; Cointreau, 2006; Sandec/Eawag, 2008; Troschinetz & Mihelcic, 2008; Wilson et al., 2012; Hoornweg and Bhada-Tata, 2012) (Table 2). Organic waste is mainly comprised of kitchen waste, such as food scraps and peeling residues, market and yard waste, wood residues and food process remains.

Table 2: Waste composition by income level (adapted from Hoornweg and Bhada-Tata, 2012)

Income level	ORGANIC (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	64	5	8	3	3	17
Middle income	56	12	11	4	3	14
High income	28	31	11	7	6	17

The increasing volumes of generated waste would generally not be a problem if waste was viewed as a resource and properly managed (UNEP, 2001e in Troschinetz and Mihelcic, 2008).

2.2 Waste collection

MSW collection is an important aspect to maintaining public health in cities. The amount of MSW collected varies widely by region and even differs widely within cities. The average waste collection rates are directly related to income level and low-income countries are reported to have low collection rates of 41% (Hoornweg and Bhada-Tata, 2012) or 45-70% (Wilson et al., 2013).

Uncollected waste leads to health and environmental risks, such as the clogging of drains, which can cause flooding. Furthermore, heaps of indiscriminately dumped wastes attract insects, rodents, domestic animals and other disease vectors and lead to leachate that contaminates surface and groundwater supplies. Uncontrolled decomposition of organic wastes also emits unpleasant odours and generates methane, a major greenhouse gas, contributing to global warming (Scheinberg et al., 2010; Zurbrügg, 2013). An environmentally sound, socially acceptable and economically feasible SWM system needs to emphasize increasing the coverage of solid waste services to all areas (Fricke et al., 2007).

2.3 Waste disposal

Waste disposal describes the activities related to the final storage of waste. Ideally, the location is a clearly designated site in which engineering and human control ensures safe storage, minimal health threats and environmental impact (Ali et al., 1999). Most LAMICs dispose of their waste through open burning, in open dumps or poorly operated landfills (Hoornweg and Bhada-Tata, 2012; World Bank, 2012). The latter two practices are associated with problems of limited land availability, the environmental pollution of water and soil through leachate and uncontrolled emissions of greenhouse gases. As dumpsites are located at the outskirts of cities, transportation and maintenance costs for waste collection companies are high (Lohri et al., 2013a). The adverse effects of poorly operated dumpsites can be alleviated by upgrading landfills and/or by reducing the waste flows destined for dumpsites.

2.4 Biowaste treatment and valorisation

Waste treatment refers to a controlled engineered process in which resources are extracted from the waste. All activities in waste management systems that have the objective of extracting and recovering resources and value from waste (material or energy) can be summarized as recycling and recovery activities (Zurbrügg, 2013). The key advantages of waste treatment are reduced quantities of disposed waste and the return of materials to the economy (Hoornweg and Bhada-Tata, 2012). Treatment and valorisation of the organic fraction is seen as one promising option to stimulate waste collection as products with economic value and high market demand can be produced from the waste, thereby driving SWM towards enhanced financial sustainability (Lohri et al., 2013a). Simultaneously, reducing the amount of waste destined for disposal also has environmental benefits. Biowaste recycling technologies can be classified according to the generated goods, such as products with fertilizing and soil amending properties (e.g., compost through controlled aerobic decomposition, Rothenberger et al., 2006), direct livestock food or indirectly through insects into protein-rich chicken- or fish-food (bioconversion through black soldier flies, Diener, 2010; Diener et al., 2011) or conversion into a product with energy value (e.g., biogas through anaerobic digestion, Mata-Alvarez, 2003; Lohri et al., 2013b; Vögeli et al., 2013; or by means of other bio- or thermo-chemical conversion processes, Garcia-Perez et al., 2010; Demirbas et al., 2011).

Biowaste-to-Energy conversion

The growing challenge of waste disposal, dwindling fossil fuel reserves and increasing environmental concerns have led to increased research interest in the utilization of waste as a supplementary energy supply and in converting it into a usable fuel substitute (Avenell et al., 1996). Particular interest in biomass-to-energy conversions is emerging, focusing on the potential of municipal solid waste, industrial waste, agricultural residues and forestry waste to create renewable energy (Srirangan et al., 2012). The potential of bio-energy is considered to be tremendous (Babu, 2008). Biowaste is a domestic resource which is not subject to world price fluctuations or the supply uncertainties of imported fuels, it generates far less air emissions than fossil fuels and, as said, reduces the amount of waste sent to landfills and decreases reliance on foreign oil (Demirbas, 2001). In their review, Singh et al. (2011) show that a waste-to-energy facility is not only possible but necessary in order to meet the demands of a growing city, improve environmental conditions, and be an example for cities in India as well as in other developing countries.

A variety of processes exist for biowaste-to-energy conversion and there are two main ways to convert biomass into valuable liquids, gases and solids. Figure 1 presents how the chemical energy stored in wastes can be recovered, namely through biochemical or thermochemical routes (Basu, 2010). The choice of conversion process depends on the type, property and quantity of biomass feedstock; the desired form of the energy; end use requirements; environmental standards; economic conditions and project-specific factors (Singh et al., 2011).

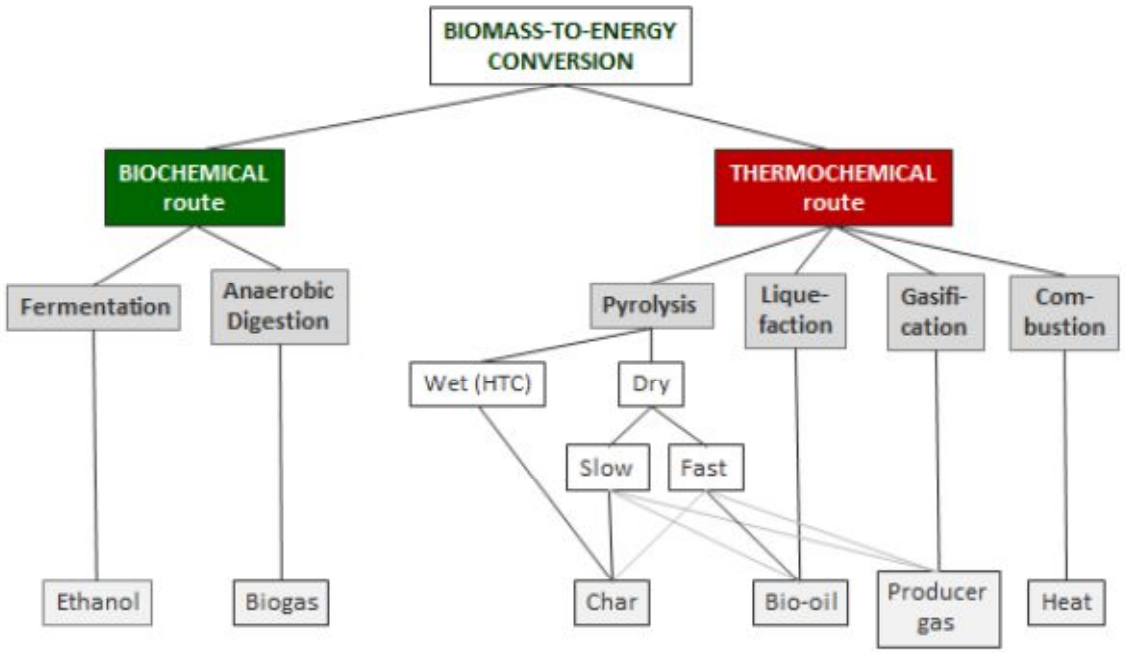


Figure 1: Two major pathways for biomass-to-energy conversion (adapted from Basu, 2010; Bridgwater and Peacocke, 2000)

- **Biochemical biowaste-to-energy conversion**

Biochemical conversion processes are based on enzymatic decomposition of organic matter by microorganisms. This process is substantially slower than thermochemical conversion, but does not require large external energy input (Basu, 2010). As microbial activity always takes place in liquid medium, biochemical conversion processes are mainly applied to wastes with high moisture levels (>50%) and a high percentage of organic biodegradable matter (>40%). The main technological option under this category is anaerobic digestion, which generates biogas, a gas mixture that mainly contains methane (60–70%) and carbon dioxide (20–40%), and a nutrient-rich digestate (De Baere, 2000; Mata-Alvarez et al., 2000; Hartmann and Ahring, 2006; Nguyen et al., 2007; Greben and Oelofse, 2009; Deublein and Steinhauser, 2010; Lohri et al., 2013b).

- **Thermochemical biowaste-to-energy conversion**

There are four main thermochemical routes for the production of fuel, namely i) direct combustion, ii) gasification, iii) pyrolysis, and iv) liquefaction. Each differs in temperature, heating rate, and the oxygen level present during treatment (Basu, 2010; Srirangan et al., 2013).

- *Direct combustion* is the oldest way of using biomass and accounts for over 97% of the world's bio-energy production (Demirbas, 2008, in Demirbas et al., 2009). It involves high-temperature conversion of biomass in air forming carbon dioxide and water vapour. In small-scale applications, such as domestic cooking appliances, it can be very inefficient, with heat transfer losses of 30-90%. This problem can be addressed through the use of more efficient stove technology (Demirbas, 2001).
- *Gasification* is a conversion process of solid carbonaceous fuel into combustible gases by supplying less oxygen than is needed for the complete combustion of the fuel. This is performed at relatively high temperatures. The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen. The gas-making processes of pyrolysis and char-gasification are separated from the burning or storage of the gas. The gas is more versatile than the original solid biomass and can be burnt to produce process heat and steam, or used in gas turbines to produce electricity (Demirbas, 2001). Micro-gasification for household cooking is a relatively new development and a detailed overview of it is given in Roth (2011). Although designed to produce gas, under some conditions gasifiers can produce reasonable yields of char and have been proposed as an alternative production route to pyrolysis for biochar (Brown, 2009).
- *Liquefaction* is a low temperature, high pressure thermochemical process, using a catalyst (e.g., alkaline hydroxides and carbonates). Due to more complex and expensive reactors and fuel feeding systems compared to pyrolysis processes, interest in liquefaction is relatively low (EUREC, 1996, in Demirbas, 2001).
- *Pyrolysis* is a process by which a biomass feedstock is thermally degraded in the absence of oxygen/air. Pyrolysis is not only an independent process, but the core reaction of all thermal processes, i.e., it is the first step in the gasification and combustion process (Babu, 2008). A broad distinction can be made between dry pyrolysis and wet pyrolysis (also called hydrothermal carbonization, HTC; see Berge et al., 2011; Libra et al., 2011; Lu et al., 2012; Li et al., 2013; Liu et al., 2013). Depending on the operating conditions, dry pyrolysis processes can be further divided into two main subclasses: slow (or conventional) pyrolysis and fast (also including flash) pyrolysis (Brown, 2009; McLaughlin, 2010; in Duku, et al., 2011).

Table 3 presents an overview of the main thermochemical processes applied in developing countries. Drying is included because it is the preliminary step of all thermochemical reactions, even if it is not a thermochemical process.

Table 3: Overview of thermochemical processes, their process parameters and products (Quicker, 2012)

	Drying	PYROLYSIS	Gasification	Combustion
Gaseous products	H_2O	CO, CH_4, C_xH_y, CO_2, H_2O, pyrolysis oils, N- and S-containing compounds	CO, H_2, CO_2, H_2O, CH_4, C_xH_y, tars, NH_y, NO_x, H_2S, COS	CO_2, H_2O, CO, C_xH_y, NO_x, SO_x
Solid residues	$C_xH_yO_z$, (N, S), ash	$C_mH_nO_k$, (N, S), ash	C, (N, S), ash	Ash, (N, S)
Parameters	Heat λ = 0 100°C	Heat λ = 0 >250°C	Air, O_2 λ = 0.2 – 0.5 >600°C	Air, O_2 λ > 1 >700°C

All processes involved in pyrolysis, gasification, and combustion can be seen in a flaming match (see Figure 2). The heat needed for pyrolysis is provided by the flame; the resulting gases and vapours burn in the luminous zone in a flaming combustion process, leaving behind char. When the match is put out, the remaining wood continues to pyrolyze, releasing smoke composed of condensed tar droplets as it cools.

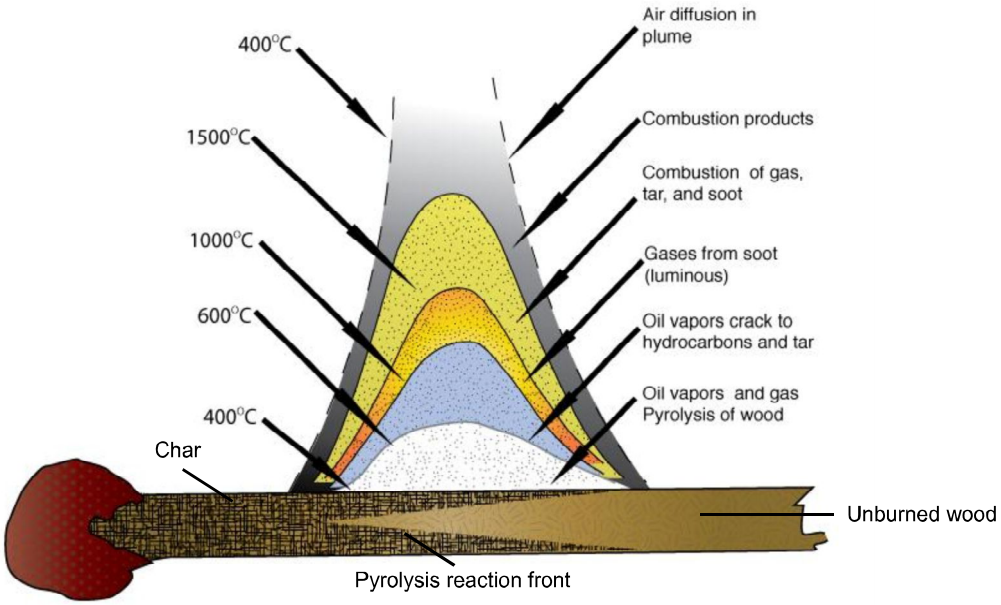


Figure 2: Pyrolysis, gasification and combustion in a burning match stick (adapted from Tom Reed, http://www.allpowerlabs.com/info/gasification-basics/gasification-explained)

Figure 3 illustrates the differences between drying, pyrolysis, gasification and complete oxidation (combustion) related to temperature and the degree of oxidation. This is indicated by the ratio between oxygen supplied to the thermal process and oxygen required stoichiometrically for complete combustion of all organic compounds (lambda, λ).

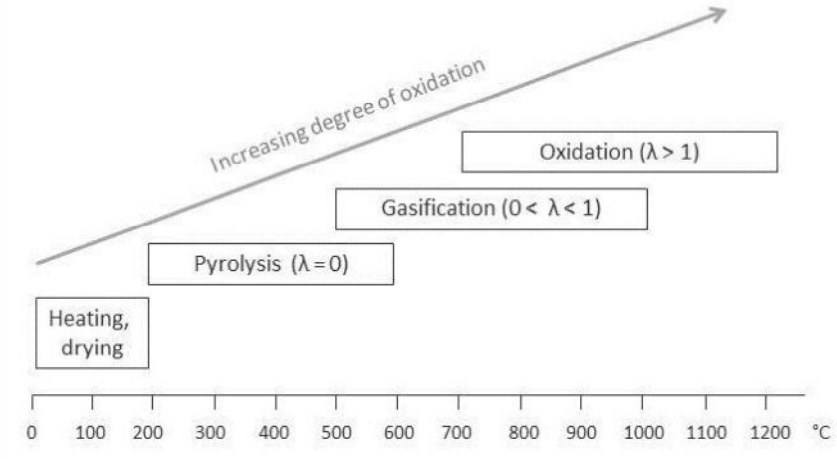


Figure 3: Phases of thermochemical transformation of biomass (Kaltschmitt et al., 2009)

At temperatures of 150 - 220°C, the first macromolecules of biomass start to get irreversibly destroyed. This degradation process occurs almost always under exclusion of oxygen (air ratio λ equals zero) and is known as pyrolytic decomposition. Even when oxygen in the atmosphere surrounding the biomass particle is present at this stage, it normally cannot reach the particle because the pyrolysis gases, produced during this process, flow out of the particle and hinders oxygen from reaching it (Kaltschmitt et al., 2009). Table 4 shows the typical product yields achieved through different modes of wood pyrolysis.

Table 4: Typical product yields (dry wood basis) obtained by different modes of wood pyrolysis (Bridgewater, 2007 in Brown, 2009; Duku et al. (2011)

Mode	Operating parameters		Liquid	Solid	Gas
	Peak temp.	*Vapor residence time*	*(bio-oil)*	*(char)*	*(syngas)*
Slow pyrolysis	Moderate (~500°C)	Long (5-30 min)	30% (70% water)	35%	35%
Intermediate pyrolysis	Moderate (~500°C)	Moderate (10-20 s)	50% (50% water)	20%	30%
Fast pyrolysis	Moderate (~500 ◦C),	Short (<2 s)	75% (25% water)	12%	13%
Gasification	High (>800 ◦C)	Moderate (10-20 s)	5% tar (55% water)	10%	85%

Table 5 presents char product yield, solid product carbon content and carbon yield of slow and fast pyrolysis in more detail and lists gasification as a point of comparison.

Table 5: Solid product yields, solid product carbon content, and carbon yield of different technologies (Meyer et al., 2011)

Process type	Typical process **temperature**	Typical **residence time**	Typical solid **product yield** on a dry wood feedstock basis [in mass%]	Typical **carbon content** of solid product [in mass%]	Typical carbon yield (mass $_{\text{carbon in product}}$ / mass $_{\text{carbon in feedstock}}$)
Slow pyrolysis	~400°C	min to days	~30%	95%	~0.58
Fast pyrolysis	~500°C	~1 s	12-26%	74%	0.2-0.26
Gasification	~800°C	~10 to 20 s	~10%		

In general, the desired product of slow pyrolysis is char, the solid residue remaining after volatile gases and vapours are released from the dry fuel material. Vapour and gaseous products can also be desirable, although these are not always recovered. Traditional processes, using earthen pits, mounds or kilns, generally involve some direct combustion of the biomass, usually wood, as a heat source. On a small-scale, char can be produced by pyrolysis in low-tech char ovens (goal: char production) and small gasifier cooking stoves (goal: heat, char as a side-product). Developments in the late 19th and early 20th centuries led to industrial scale char production processes, using large retorts operated in batch or continuous modes. These allow for the recovery of organic liquid products and the recirculation of gases to provide process heat, either internally or externally (Brownsort, 2009). An encompassing review of the science behind charcoal making is given by Antal and Grønli (2003) and more details are presented in Chapter 4 of this report.

Fast pyrolysis aims at maximizing liquid product yield and generally requires feedstock with small particle sizes and a design that quickly removes the vapours from the hot solids. There are a number of different, quite complex reactor configurations, such as ablative systems, fluidized beds, mechanically stirred or moving beds and vacuum pyrolysis systems, which can achieve this (Brownsort, 2009). Fast pyrolysis has been extensively reviewed by Bridgwater (e.g., Bridgwater et al., 1999; Bridgwater and Peacocke, 2000). Very fast pyrolysis is sometimes referred to as 'flash pyrolysis' (Demirbas and Arin, 2002, in Brownsort, 2009) usually in the context of laboratory studies involving the rapid movement of substrate through a heated tube under gravity or in a gas flow. Higher temperatures and shorter residence times are required, however, the main product distributions are similar to fast pyrolysis (Brownsort, 2009).

Flash carbonization is a different process, involving partial combustion of a packed bed of biomass in a pressurized reactor with a controlled air supply. A high yield of char and gas are reported with no liquid product formed under the reaction conditions (Antal et al., 2003). The technology is being commercialized by Carbon Diversion Incorporated (CDI, 2009; Brownsort, 2009).

3 Cooking energy in low- and middle-income countries

Access to affordable and reliable energy services is fundamental to reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth (OECD/IEA, 2011). Yet many developing countries face a severe energy crisis with limited access to energy and cooking fuel consumption which is highly unsustainable, thereby posing risks to human and environmental health. A household in developing countries uses approximately 90% of the energy that it consumes for cooking (Rajendran et al., 2013). There are currently about 2.7 billion people in developing countries, approximately 40% of the global population, who rely primarily on biomass for cooking and more than 95% of these people are either in Sub-Saharan Africa or developing countries in Asia (Table 6). According to the latest projections, there will be 2.7 billion people in 2030 that will rely on traditional biomass for cooking (OECD/IEA, 2011).

Table 6: People relying on traditional biomass for cooking by region, 2009 (OECD/IEA, 2011)

Region and country		People relying on traditional biomass for cooking (million)	Share of population (%)
Africa	Nigeria	104	67%
	Ethiopia	77	93%
	DR of Congo	62	94%
	Tanzania	41	94%
	Kenya	33	83%
	Other Sub-Saharan Africa	335	74%
	Total (Africa)	*657*	*65%*
Developing Asia	India	836	72%
	Bangladesh	143	88%
	Indonesia	124	54%
	Pakistan	122	72%
	Myanmar	48	95%
	Rest of Developing Asia	648	36%
	Total (Developing Asia)	*1921*	*54%*
Latin America	*Total (Latin America)*	*85*	*19%*
Developing countries	**Total**	**2662**	**51%**

The still massive reliance on solid biomass energy in Sub-Saharan Africa (SSA) countries and its significance in terms of employment generation, urban-rural revenue flow, domestic energy security and green economic development potential heavily contradicts the low profile of biomass in national energy policies (Owen et al., 2013). It is widely viewed as a retrogressive source of energy that degrades the environment and engenders poverty, and is considered as an indicator of energy poverty, whereas access to modern energy services - including electricity and clean fuels - is seen as an important contribution to achieve the Millennium Development Goals (MDGs) (UNDP, 2005). Therefore, although there is growing global concern and mobilization around household energy access issues (Ekouevi and Tuntivate, 2012), efforts toward providing clean cooking facilities, including charcoal systems, that are more environmentally sustainable, energy efficient and have lower health risks compared to traditional biomass cook stoves, are often thwarted by a generally entrenched anti-biomass sentiment at high levels of governments (Owen et al., 2013).

3.1 Charcoal as primary cooking fuel

Charcoal is the residue of solid non-agglomerating organic matter, of vegetable or animal origin that results from carbonization by heat in the absence of air at a temperature above 300°C (Emrich, 1985). Charcoal is the main cooking fuel for millions of households in urban and peri-urban Sub-Saharan Africa (SSA; IEA, 2009). Charcoal production in Africa was 29 Mton in 2011 (FAOSTAT, http://faostat3.fao.org/faostat-gateway/go/to/search/charcoal/E). Brazil is by far the largest char producer in the world, producing 9.9 million tons/year. Other important char producing countries are Thailand (3.9 million tons/year), Ethiopia (3.2 million tons/year), Tanzania (2.5 million tons/year), India (1.7 million tons/year) and Democratic Republic of Congo (1.7 million tons/year) (Garcia-Perez et al., 2011).

Approximately 80% to 90% of urban households in the SSA region depend on unsustainable sources of charcoal for cooking and heating (Mwampamba et al., 2012). Fuel switching from firewood to charcoal is common in developing countries, particularly in urban areas. This growing demand for charcoal has generally been driven by high population and urbanization growth, making charcoal the major primary source of energy for most urban dwellers for at least another generation (WEO, 2010; Arnold et al., 2006; Zulu and Richarson, 2013). It is estimated that for each 1% increase in urbanization, there is a 14% increase in charcoal consumption (Hosier et al., 1993). In Dar es Salaam, Tanzania, for example, the proportion of households using charcoal climbed from 47% in 2001 to 71% in 2007 (World Bank, 2009). The latest data show that while charcoal is consumed by 94% of urban households either alone or mixed with other fuels, it is used as first choice cooking fuel by about 78% of the households in Dar es Salaam City (Felix and Gheewala, 2011). However, data reliability is generally low, as 90% of the charcoal transported into Dar es Salaam City went unreported in official records (Norconsult, 2002). In addition, the charcoal sector rarely generates data that capture production and consumption volumes. This is largely due to the clandestine nature of production, poor regulation and informality of the sector. In addition, inconsistencies between IEA and FAO estimates of national charcoal production for the year 2010 for selected countries have been observed (Mwampamba et al., 2013).

Using charcoal for cooking is advantageous for several reasons: it has about double the energy content of fuel wood, i.e., higher heating value of approximately 25-30 MJ/kg of completely carbonized charcoal with about 5% moisture content as compared to about 15-16 MJ/kg of firewood with roughly 15% moisture content on dry basis (Meyer, 2009; Felix and Gheewala, 2011). Furthermore, charcoal is available throughout the year, is relatively light, clean and safe (burns with less smoke compared to firewood) and can be stored easily and for long periods because it is not damaged by rain or moisture. Charcoal also is characterized by low input, production and consumer costs; it can be purchased on the local market in small quantities and can be burned in inexpensive stoves. Charcoal costs less than kerosene, LPG, and electricity in most cities in developing countries (Bailis et al., 2003; Ellegàrd and Nordström, 2003; Beukering et al., 2007; Seidel, 2008; Sebokah, 2009; Akpalu et al., 2011; Kifukwe, 2013; Zulu and Richardson, 2013). Charcoal is not only the main source of household energy for the majority of the urban population, it is also a significant contributor to national energy balances and an important source of household incomes (Arnold et al., 2006). Charcoal alone was estimated to contribute US$ 650 million annually to Tanzania's economy (US$ 350 million in Dar es Salaam alone), compared to US$ 700 million of foreign direct investment in Tanzania in 2010, and almost 6 times the combined value of coffee and tea production (World Bank, 2009; Sander et al, 2013). Thus, the charcoal sector in Tanzania provides income to several hundred thousand households in both urban and rural areas (World Bank, 2009). The production of charcoal is almost a zero-cost activity in rural areas and charcoal is often the most commercialized resource in urban areas (Luoga et al., 2000; SEI, 2002; Arnold et al., 2006; Kambewa et al., 2007; Seidel, 2008; Felix and Gheewala, 2011). The most important factor encouraging people to start producing charcoal is the lack of alternative income-generating activities and the fact that charcoal is a cash product, with a large market ready to absorb the entire production (Beukering et al., 2007). A general overview of the benefits of biomass energy for SSA countries is presented in Owen et al. (2013). However, charcoal remains "the black sheep in Africa's renewable energy family" (Chaix, 2011) with a negative image as a dirty, unhealthy, and primitive fuel (Mugo and Ong, 2006; IIED, 2010; Sepp, 2010; Zulu, 2010).

3.1.1 Charcoal chain

The primary actors in the charcoal value chain are producers, wholesalers, retailers, and transporters (Osemeobo and Njovu, 2004; Kambewa et al., 2007; Zulu and Richardson, 2013; see Figure 4). The vast majority are farmers who are engaged in charcoal production in addition to agriculture and who produce charcoal from trees felled during land clearing. The charcoal market plays a significant role in generating seasonal and full-time employment in regional value chains. Transport costs may be the major factor determining the price of charcoal and comprises 60-70% of the final price (Mahu, 2006). Another problem associated with transport is the loss of charcoal due to breakage during packaging and transport. It is estimated that this loss accounts to 20% of the total charcoal produced (Seidel, 2008).

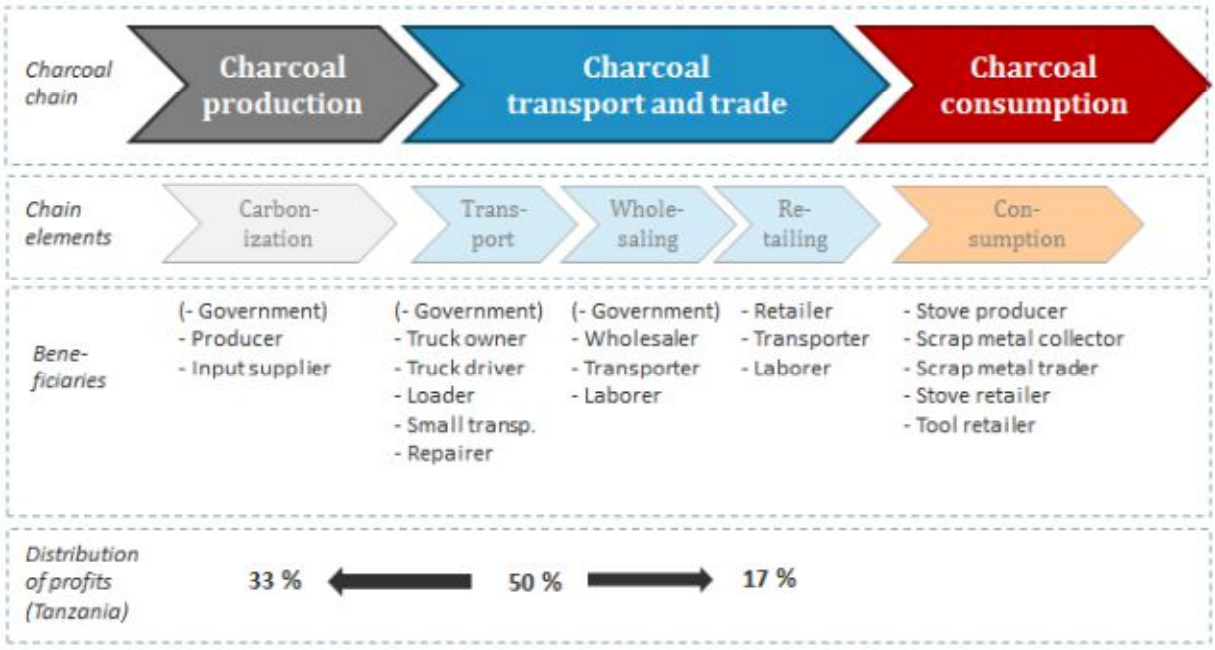


Figure 4: Charcoal chain (adapted from Beukering et al., 2007; Ekouevi and Tuntivate, 2012)

3.1.2 Energy ladder vs. energy stacking

It is generally assumed that consumers shift to more efficient, convenient and cleaner energy systems as their income rises (Masera et al., 2000; UNDP, 2000; WEO 2009). A common model to describe household fuel choices in developing countries is the "energy ladder" concept which ascribes differences in energy-use patterns between households to variations in economic status (Hosier and Dowd, 1987; Leach 1992; Barnes and Floor, 1996). The energy ladder theory postulates a linear movement with three distinct phases (see Figure 5). As household incomes increase, and individuals and countries develop economically, people's energy preferences move up on the energy ladder. Families that gain socio-economic status abandon technologies that are inefficient, more costly and polluting and move from universal reliance on 'inferior' biomass fuels (e.g., dung and fire wood) through charcoal – the 'transition fuel' in the second phase – to modern cleaner alternatives, including LPG and electricity in the third and last phase (Hosier and Dowd, 1987; Leach and Mearns, 1988; Bruce et al., 2000; UNDP, 2000; Campbell et al., 2003; Heltberg, 2004; Arnold et al., 2006).

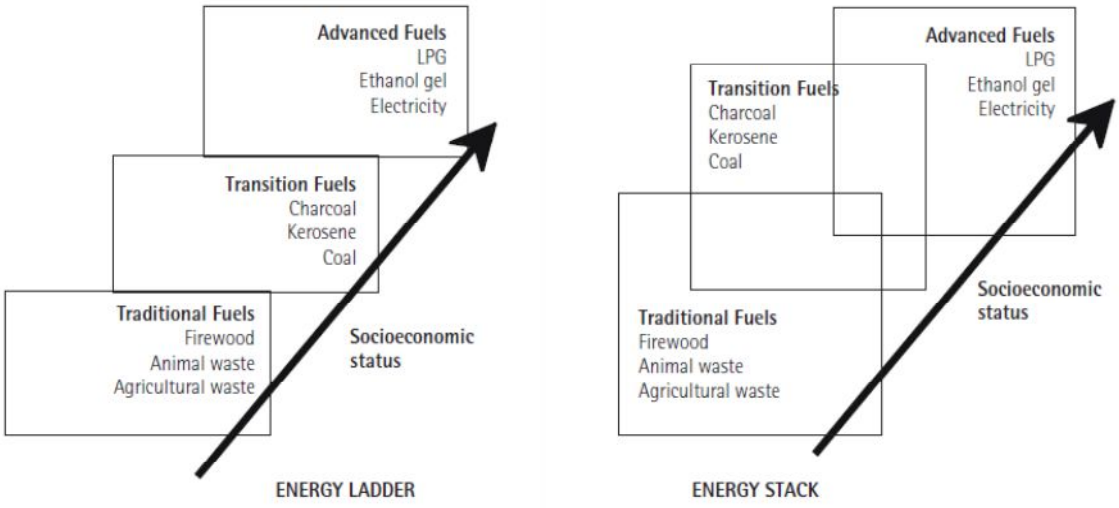


Figure 5: Comparison of energy ladder and energy stack theory (World Bank, 2009; adapted from Schlag and Zuzarte, 2008)

However, the energy ladder theory is generally considered too simplistic and a growing body of empirical studies on household energy use show that the energy transition does not occur as a series of simple, discrete steps; instead, multiple fuel use is more common (Leach, 1992; Zein-Elabdin, 1997; Davis, 1998; Hulscher, 1998; Masera et al, 2000; Karekezi and Majoro, 2002; Brouwer and Falcao, 2004; Heltberg, 2004; Elias and Victor, 2005; Martins, 2005; Shine et al., 2005; Arnold et al., 2006; Hiemstra et al., 2008; Hiemstra et al., 2009; Maconachiea et al., 2009; Zulu, 2010; Kroon et al., 2013). This concept of complementing traditional with modern energy sources rather than replacing them is referred to as 'energy stacking' (Masera et al., 2000; ESMAP 2003; Bacon et al., 2010). Apparently, putting too much faith in the 'energy ladder' or 'energy transition' theory has undermined realistic, proactive policy-making on charcoal. Recent evidence shows that for Africa, several obstacles make the theorized energy transition proceed at a slower pace than anticipated given persistently high levels of poverty (affordability), infrastructure problems to access main alternatives (LPG, kerosene and electricity), and cultural factors. Findings, therefore, point to an incomplete transition and continued dependence on charcoal within a fuel mix in the foreseeable future (Hosier and Dowd, 1987; Masera et al., 2000; Martins, 2005; Chambwera and Folmer, 2007; Hiemstra-van der Horst and Hovorka, 2008; Zulu, 2010).

In general, fuel wood and charcoal remain primary cooking fuels because people prefer to cook with the lowest-cost energy sources (Davis, 1998; Madubansi and Shackleton, 2007; Howells et al., 2005; Arthur et al., 2010). High income levels alone may not be a sufficient determinant of fuel switching. Other factors, such as reliability of supply, safety, and taste preferences of food cooked using tradition fuels, may influence household preferences (Ekouevi and Tuntivate, 2012). Evidence from Uganda (GVEP, 2010) and Tanzania (Mwampamba et al., 2013) show that, contrary to the popular view that charcoal is a fuel for low-income urban dwellers, a high percentage of high-income groups also regularly use charcoal, i.e., charcoal is consumed by all socio-economic categories of urban dwellers.

Current policies that prioritize fuel switching are unrealistic and incomplete, failing to recognize the realities of actual energy costs, future consumption trends, and the significant potential offered by biomass energy. However, in response to the energy crises, some SSA countries have been re-evaluating their energy policies to develop biomass energy strategies (BEST) (Owen et al, 2013). These strategies are meant to: (i) ensure a sustainable supply of biomass energy, (ii) increase efficient and effective use of biomass energy, and (iii) promote access to appropriate, alternative sources of energy. Briquetting in general, and charcoal briquettes in particular, could contribute to attaining all of these objectives within the framework of more realistic, pragmatic and biomass-oriented energy policies (Mwampamba et al., 2012).

3.2 Environmental consequences

The impacts of charcoal on ecosystems occur at every stage in the production-consumption chain (Chidumayo and Gumpo, 2012). The consequences include adverse effects on the environment, on biodiversity, regional and global climate, agricultural productivity and watershed management (Beukering et al., 2007; Msuya et al., 2011). There is particular concern about the sustainability of charcoal production (Shackleton et al., 2006) because, despite charcoal stoves being more efficient than traditional firewood stoves, a high quantity of fuel wood is required for charcoal production (Brouwer and Falcao, 2004; Mwampamba, 2007; Zulu, 2010). Yet, in contrast to common belief, charcoal production as such is not a driver of deforestation (e.g., Chidumayo, 1993; Hosier, 1993; Okello et al., 2001; Bailis, 2009). Deforestation is fuelled by a set of drivers, the importance of each is highly disputed (Chidumayo, 1997).

During the 1970s and early 1980s, the harvesting of biomass was mistakenly portrayed as the leading driver of global deforestation under the 'wood fuel gap' theory (Mahiri and Howorth, 2001). Although the expected fuel wood gap was not observed (Dewees, 1989; Foley, 2001; Sampson et al., 2005; Arnold et al., 2006; IEA, 2006), the fuel wood crisis narrative is still widely established in international organizations, governments and NGOs, despite the lack of empirical evidence (Arnold et al., 2006; Bensel, 2008; van der Hiemstra et al., 2009; Zulu, 2010). Nowadays, there is a broad consensus among scientists that a global fuel wood crisis will not occur and that future stocks will satisfy the increasing demand. It is further widely accepted that the clearing of land for arable and pastoral agriculture is the main cause of deforestation rather than the use of wood for energy (Ekouevi and Tuntivate, 2012). Still, it must be recognized that

local fuel wood scarcities occur, as was for instance reported in regions in India, Tanzania and in Southern Africa (ESMAP, 1999; Luoga et al., 2000; Geist and Lambin, 2002; SEI, 2002; Scholes and Biggs, 2004; Mwampamba, 2007; Clancy, 2008; Ahrends et al., 2010).

Yet, most scientists do agree that increases in charcoal production and demand have caused significant changes in forest ecosystems, and that the associated environmental degradation and soil erosion have led to lower agricultural productivity around numerous rapidly expanding African cities (Ribot, 1999; Luoga et al., 2000; SEI, 2002; Malimbwi et al., 2005; Arnold et al., 2006; Kambewa et al., 2007; Mwampamba, 2007; Lupala, 2009; Alem et al., 2010; Giliba et al., 2011a, 2011b). Thus, although it is now accepted that biomass harvesting is only a minor contributor to deforestation (Openshaw, 2011), charcoal extraction can be a first step towards forest degradation, particularly when it is followed by intensive grazing (Hosier, 1993) or by conversion into agricultural fields (Bailis, 2009) or when charcoal extraction is too frequent (Maes and Verbist, 2012).

3.3 Enhancing sustainability

Throughout the entire charcoal chain from production to use, there are possibilities to increase sustainability. This starts with community-based forest management, in which sustainable harvesting can be guaranteed, followed by improved methods for charcoal production, and ends with its use in improved stoves (Bailis et al., 2003). Improving the sustainability of charcoal is considered as the most effective measure possible for improving the sustainability of household cooking energy in developing countries and should be a key priority (Girard, 2002; SEI, 2002; Bailis, 2003; Mwampamba, 2007; Sebokah, 2009; Bailis, 2009; Syampungani et al., 2009; Zulu, 2010).

According to Maes and Verbist (2012), there are two distinct policy alternatives to increase the sustainability of cooking in developing countries. The first option is to climb the energy ladder and switch from solid biomass fuels to liquid fossil fuels (LPG or kerosene), biogas or electricity. As this largely avoids the severe health impacts caused by traditional biomass use, this option is considered the most desirable by numerous countries and by international organizations.

However, as described above, a large-scale switch to liquid fuels or electricity is unrealistic in most developing countries due to the lack of necessary requirements, infrastructure, economics, and cultural barriers. Thus, the second policy option, increasing the sustainability of the current traditional biomass system, must be considered. This can be realized by an integrated approach, in which national and regional biomass energy policies are adapted that aim at: i) improving the supply of wood by afforestation projects and sustainable natural resource management, ii) increasing the efficiency of charcoal production by promoting improved production technology and iii) promoting improved, fuel efficient stoves (Seidel, 2008; Maes and Verbist, 2012).

3.3.1 On the policy level

As most charcoal is harvested without paying for the raw material (wood) or licenses, and taxes are largely evaded, the cost of charcoal to the consumer does not reflect its real value (World Bank, 2009). This largely hinders investment in improved conversion technologies, long-term sustainable forest management, or establishment of plantations and woodlots. It is thus essential to improve the regulatory and fiscal frameworks of the sector, otherwise the market price of legal and sustainably produced charcoal will always be undercut by unregulated and unsustainable products (World Bank, 2009).

As a response to the negative effects of charcoal production, some African states attempted to ban charcoal production at one stage (e.g., Malawi, Mauritania, Kenya, and Tanzania). However, this proved to be counterproductive as the producers were forced to produce charcoal in secrecy, which prohibited the use of improved technologies (Seidel, 2008). One example of such an initiative was a two-week charcoal ban in January 2006 in Tanzania (ESD, 2007; Malimbwi et al., 2007; van Breukering et al., 2007), which was imposed by the Minister for Natural Resources and Tourism for fear that rapid deforestation was the impetus behind declining hydroelectric capacity, causing a severe energy crisis in 2005–2006 (World Bank, 2007a, 2007b; HELIO International, 2009; Shemsanga et al., 2010). Since there were no affordable and

reliable alternatives to charcoal for most urban consumers, production continued during the ban, yet under more difficult conditions. Because charcoal trading was officially illegal, transactions along the charcoal value chain had to be carried out under highly clandestine conditions (i.e., through back routes or travelling at night). Although not formally documented, the ban led to an increase in corruption, i.e., the paying-off of law enforcement staff at checkpoints. The higher transaction costs, including a risk premium for the possibility of detection and confiscation of the illegally produced and traded charcoal, were simply passed on to the consumer, which led to charcoal prices nearly doubling during the time of the ban (from around US$ 11 per bag before the ban to US$ 20 during the ban, in 2006 prices and exchange rates) and remained at higher levels, even after the ban was lifted (US$ 14 per bag after the ban). Overall, Tanzania's experience with the ban on charcoal represents a policy experiment, exposing the limited effectiveness of the formal governance framework of Tanzania's charcoal sector. A ban on charcoal was formally imposed and effectively ignored. Unsustainable charcoal production continued, with prices spiralling upwards (Malimbwi et al., 2007; World Bank, 2009 in Sanders et al., 2013).

Such and similar bans have increased production costs, reduced market access, driven the charcoal market 'underground,' increased corruption, denied governments much needed tax revenues from potential regulated exploitation, and undermined charcoal's potential as a poverty reduction tool in many SSA countries (Dewees, 1995; Angelsen and Wunder, 2003; Kambewa et al., 2007; World Bank, 2009). For instance, Tanzania and Malawi lost at least US$ 100 million and 17.3 million in uncollected charcoal-based revenues, respectively (World Bank, 2009; Zulu, 2010; Zulu and Richardson, 2013)

Three core issues have been identified that constitute the heart of the incentive problem to stimulate a more effective and sustainable management of the charcoal sector: (i) lack of fiscal empowerment, (ii) lack of legal empowerment, and (iii) low capacity for policy implementation and enforcement (Sanders et al., 2013).

3.3.2 Increased efficiency in charcoal production and consumption

Saving forest woodlands can be enhanced by increasing the efficiency of charcoal production and consumption.

- **Kiln conversion efficiency**

The conversion of biomass to char plays a small but crucial role in the biomass/biowaste-to-charcoal value chain. The success of the carbonization process is the efficiency of the kiln, defined as the mass yield of char, expressed as a percentage of the dry mass of feedstock substrate initially placed in the kiln. Kiln or retort efficiency is also referred to as carbonization efficiency, conversion efficiency or char yield. The kiln efficiency (or char yield provided by a kiln) is given by equation 1:

$$y_{char} = \frac{m_{char}}{m_{bio}} \qquad (1)$$

where m_{char} is the dry mass of charcoal produced in the kiln and m_{bio} is the initial dry mass of the biomass feedstock loaded into the kiln (Antal and Grønli, 2003). Energy input to the kiln is provided via biomass either burned inside the kiln (to provide direct heating) or externally outside (indirect heating). Biomass, which is burned to provide direct heating, needs to be included in efficiency calculations. Thus, in comparing net yields, the output weight of the char should be compared with the weight of all dry feedstock consumed in the process, including feedstock consumed to drive pyrolysis (Taylor, 2010). But this representation of the efficiency of the carbonization process is intrinsically vague because it does not reflect the fixed-carbon content of char product, which widely varies. It is relevant to know that the conversion efficiency decreases when peak temperature increases, because the tar fraction is lost, but that the quality of the product improves (Antal and Grønli, 2003). A more meaningful measure of the carbonization efficiency is given by the fixed-carbon yield (y_{fc}) in Equation 2:

$$y_{fc} = y_{char} * \frac{\%\, fc}{(100 - \%\, feed\ ash)} \qquad (2)$$

where *fc* is the fixed carbon content of char as measured by ASTM Standard 5142 (ASTM, 2004) and *% feed ash* is the percentage ash content of the feedstock (Antal et al., 2000). This yield represents the efficiency realized by the pyrolytic conversion of the ash-free organic matter in the feedstock into a relatively pure, ash-free carbon. A perfect kiln would have fixed carbon yield equal to the solid carbon yield predicted by thermodynamic equilibrium (Brown, 2009).
Finally, the energy conversion efficiency of a kiln can be defined by Equation 3 as:

$$\eta_{char} = y_{char} * \frac{HHV_{char}}{HHV_{bio}} \qquad (3)$$

where HHV_{char} is the higher heating value of the charcoal and HHV_{bio} is the higher heating value of the feedstock (Antal and Grønli, 2003).

Char yields are affected by the following factors (Beukering et al., 2007; Taylor, 2010):

- dryness of the feedstock
- effectiveness of kiln heat-retaining insulation or heat shields
- efficiency with which heat from heating fuel and combustion of pyrolysis gases are transferred into the feedstock
- peak pyrolysis temperature (and related volatile content)
- amount of re-deposition of volatiles onto the char product (secondary reaction)
- monitoring of the carbonization process
- skills of the producers

Pit or earth-mound kilns, traditionally used in most developing countries (Bailis et al., 2005) for charcoal production (Schenkel et al., 1998; Adam, 2009), reach conversion efficiencies of 10–15% (Bhattacharya et al., 2002; Antal and Grønli, 2003; Sebokah, 2009). The most efficient non-industrial system available in developing countries has a conversion efficiency of 35% (Maes and Verbist, 2012).

Several improved kilns have been developed. Many projects have attempted to overcome the challenge of low efficiency levels by promoting more efficient kilns for charcoal production, but adoption rates have been disappointing. The reasons for this are mainly found in the informal - and often illegal - nature of charcoal production (World Bank, 2009). Additionally, the dissemination of improved kilns has proved to be difficult because they are economically viable only when wood has to be bought (Seidel, 2008).
The improvement of these systems lies in increasing the conversion efficiency through: (i) better air draft using metal pipes, (ii) careful stacking of the wood and placement of air inlets and (iii) kiln insulation using bricks or metal plates. In general, the higher efficiency of improved systems comes at the price of higher material and equipment costs and of reduced flexibility, in terms of reactor volume, feedstock size and portability. Unfortunately, the greenhouse gas emissions of improved systems remain relatively high (Maes and Verbist, 2012). However, improved, low-cost retort kilns utilize hot exhaust gases to pre-dry the substrate or provide energy for the carbonization process, rather than emitting these directly to the atmosphere (Owen et al., 2013). It is important to note that additional costs related to improved systems are only feasible under a formalized charcoal sector, fiscal incentives may be required to justify higher investments, and sufficient monitoring for compliance is needed (World Bank, 2009).

- **Improved stoves**

It is well known that improved cook stoves can reduce indoor air pollution and net greenhouse gas emissions, reduce fuel consumption and, thus, partially relieve women and children from the burden of wood fuel collection. Based on the lessons learnt from previous improved stove programs, the following recommendations for successful programs are important: i) stove design (understanding users' needs such as cleanliness, time saving, fuel flexibility and compatibility, cooking habits, safety, comfort, cost and durability, aesthetics and familiarity), and ii) project sustainability, i.e., finding the balance between commercialization and funding (Maes and Verbist, 2012).

Compared to the thermal efficiency of firewood stoves (10% in traditional three-stone fires and 13-40% in improved wood stoves), the thermal efficiencies of charcoal stoves used for cooking in developing coun-

tries range from 12 to 27% (Bhattacharya et al., 2002), although efficiencies up to 46% have been recorded in improved stoves (Koyuncu and Pinar, 2007).

In 2010 the UN Foundation initiated the Global Alliance for Clean Cookstoves, with the intention of launching an effort to disseminate and increase adoption of improved cooking technology on a massive, global scale, based on lessons learnt from previous programs and recent technological improvements (Global Alliance for Clean Cookstoves, 2012). However, the effort is mostly directed towards the use and dissemination of stoves, with little consideration given to the production and sustainability of biomass fuels (Owen et al., 2013).

3.3.3 Alternative substrates and briquetting

An alternative to the unsustainably produced wood-based charcoal is charcoal made from organic waste products, either compressed first and then carbonized or carbonizing biowaste and then briquetting it. Briquettes can be made from a number of different small-particle feedstocks, including agricultural field and processing residues and forestry residues. Charcoal briquettes can be used as a direct substitute for wood-based charcoal and are seen as an attractive means to partly alleviate the traditional fuel crises faced in many developing countries (Bhattacharya et al., 1990). In Tanzania, a number of enterprises currently produce briquettes, and while the price for charcoal briquettes were less than half that of conventional charcoal in 2007 (ESD, 2007 in World Bank, 2009), they have increased since but remain lower than wood charcoal. In December 2013 charcoal briquettes made from agricultural waste in Dar es Salaam were sold for 600 TZS per kg. For comparison, traditional wood charcoal was sold for 1400 TZS/bag (0.9-1.3 kg) and for 47'500 TZS/bag (80-120 kg) (ARTI-Energy, 2013). Due to higher ash content of some biowaste, the calorific value of charcoal briquettes formed is lower and combustion characteristics are slightly different compared to wood-charcoal.

Global annual production of agricultural residues is estimated to be more than 500 million tons (Mt) (Sanchez, 2009). Estimates from SSA indicate that 1000 Mt and 140 Mt are generated annually from the forestry and agricultural sectors, respectively (Dasappa, 2011).Many developing countries have a wide variety of agricultural residues in significant quantities in the form of field- and agro-processing residues, of which large amounts are vastly unutilized (Demirbas, 2001). Yet, the use of crop residues for fuel in countries with extreme wood fuel shortages seems at odds with measures to enhance agricultural productivity (Owen et al., 2013). The problem has been highlighted as a potential incompatibility of using significant amounts of biomass waste for bioenergy production whereas sustainable forms of agriculture rely on agricultural waste inputs as soil amendment and for their nutrient balance as a substitute for inorganic fertilizers (Muller, 2009). Therefore, to preserve the soil quality only a small portion of the crop residues should be used for energy generation. This portion depends on diverse factors (e.g., crop rotation, fertilizer use) and is estimated in different studies by a (sustainable) recovery rate of 50% to 70%, while other sources use more conservative rates, such as 20% or 35% (Stecher et al., 2013). This crop waste portion can be converted into energy, and energy potential can be estimated by using specific heating values; a uniform number of 17-18 GJ/t (Stecher et al., 2013).

- **Briquetting**

Briquetting, defined as the process of reconstituting fine biomass materials into larger particles, typically entails a mechanical compaction process. This is a well-known technology and has been widely used in developed and developing countries, although for different applications. In developed countries, densified biomass fuels (briquettes and pellets) are mainly used for industrial energy applications and space heating, whereas in developing countries the main market is for household fuel (Rajabu and Ndilanha, 2013).

Energy density can be increased further by carbonizing the biomass before or after compaction (Bhattacharya et al., 1999). When carbonizing before briquetting, cohesion is achieved by low-pressure agglomeration with the use of binders (e.g., molasses, cassava residues), medium-pressure compaction with a lower binder percentage, or high-pressure compaction with little or no binder (Mwampamba et al., 2012). In principle, briquettes made from various types of biomass can be used as fuel without any subsequent carbonization. The decision to carbonize depends on the application (GVEP, 2012). Compacting waste into briquettes lowers transportation costs, facilitates handling and increases access to more dis-

tant markets (Mwampamba et al., 2012). In SSA, growing interest in briquettes is caused by increasing concern with the unsustainability of traditional forest-based wood charcoal production systems and the imminent need for alternative fuels. However, despite the clear advantages of charcoal briquettes that includes price, environmental sustainability, consistent quality and the potential for product standardization, their uptake as a substitute for wood charcoal in SSA remains limited. Charcoal briquettes have a huge market in urban areas, but have the disadvantage of consuming a large amount of heat energy in the carbonization process (Rajabu and Ndilanha, 2013). Official estimates of the volume of briquette production in the region are unavailable and difficult to generate because of the isolated and uncoordinated nature of briquetting initiatives, and biomass energy sector in general. Although the last decade has seen an increase in charcoal briquetting initiatives in East Africa, large-scale charcoal briquette production in the developing world is mostly concentrated in Asia (Mwampamba et al., 2012).

Briquettes produced with *charcoal dust* can be used as a supplement or alternative to charcoal and in this way they make use of a waste product. Yet, it is a matter of debate how far charcoal dust briquettes can be considered sustainable, since they rely on the existence of a charcoal industry that most agree is currently operating unsustainably (GVEP, 2010). A study in Uganda revealed that in the foreseeable future, charcoal dust briquette use could displace up to 5-10% of present charcoal consumption (GVEP, 2010).

Mwampamba et al. (2012) give a summary of factors affecting the charcoal briquette industry in SSA and provide an overview of the seven main charcoal briquetting enterprises in Kenya, Tanzania, Uganda and Rwanda. At least 10 charcoal briquetting initiatives are known in East Africa, of which three companies are operating on a relatively large-scale (i.e., producing >20 t/month), independent, profit-making basis. They are located in Nairobi (Kenya), Kigali (Rwanda, and Tanga (Tanzania). The former two produce briquettes from charcoal dust and fines salvaged from urban charcoal traders. Producing briquettes from charcoal dust, rather than from raw biomass residues, eliminates the carbonization process and enables the low price of wood charcoal. The almost exclusive use of char dust for briquetting is due to the fact that the carbonization and subsequent briquetting of biowaste feedstock has yet to be done in the region, requires modification to machinery, additional skills and more research (Mwampamba et al., 2012).

Since charcoal briquetting burns with the same combustion phenomena and stoves as wood-based charcoal, it represents a complementary fuel, rather than a fuel switch. Charcoal briquette use can reduce the amount of wood-based charcoal consumption by an individual household, without requiring significant equipment changes. Therefore, it generally does not require major investments in new technologies and - depending on the availability - households can easily switch back and forth between the two types of charcoal. Due to this complementary nature, briquetting is not included in the discussion regarding the economic costs of fuel switching (World Bank, 2009). Table 7 provides an overview of the general differences between wood-based charcoal and charcoal briquettes.

Table 7: Differences between wood charcoal and charcoal briquettes (adapted from Mwampamba et al., 2012)

	WOOD charcoal	CHARCOAL briquettes
Raw material	Wood	Agricultural & specific urban biowaste, char dust
Location of production	Almost exclusively rural	Peri-urban and urban
Efficiency of production	Traditional earth mounds and pits and metal and brick kilns: 15-25%	Drum kilns and retorts: 15-20%
Energy value	31-33 MJ/kg	22-29 MJ/kg
Ash content	<5%	10-30%
Price	100-300 $/t	150-250 $/t
Ease of lighting	Easy to light	Harder to light (due to higher ash content)
Length of burn	Fast burning (high energy & low ash)	Slow burning (higher ash content)
Extinguishability	Can be put out for later re-use	Generally crumbles if put out, (depending on stage of combustion) can be put out with sand for later re-use

4 Carbonization

Carbonization, or char-making, is a slow pyrolysis process, which has been used since the dawn of civilization (Demirbas, 1999 in Demirbas, 2001). The earliest known example of the use of charcoal, produced as an unintentional residue from cooking fires, can be found on the cave drawings of Cro-Magnon man approximately 38'000 years ago (Antal and Grønli, 2003).

Etymologically *pyrolysis* derives from the Greek words *pyr* (= fire) and *lysis* (= loosening, separating, breaking apart). Thus, pyrolysis refers to the thermal decomposition (breakdown under heat) of biomass into primarily a carbon-rich solid residue (char), and secondarily into gases and liquids. This thermal process is generally characterized by a slow heating rate (5-7K/min), long solid and gas residence times, and relatively low temperatures (350-550°C) in a largely inert, i.e., oxygen-deficient environment (Goyal et al., 2008). The term 'char' is generally used for the solid product that arises from the thermal decomposition of any organic material, whereas 'charcoal' is the solid, carbon-rich residue left when organic solids, mostly woods, are heated in an environment with limited oxygen. 'Charcoal' is intended for use as a fuel (e.g., for cooking or industrial purposes), while 'biochar' is carbonized biomass intended for use as a soil amendment (Taylor, 2010). The process of carbonization removes most of the volatile content that is responsible for smoke emissions during the burning of raw biomass when it is not properly mixed with air (Brown, 2009).

4.1 Input requirements

Biomass generally refers to any organic materials derived from plants or animals (Loppinet-Serani et al., 2008 in Basu, 2010). Biomass is a complex mixture of organic materials, i.e., carbohydrates, fats and proteins, along with small amounts of minerals, such as sodium, phosphorus, calcium and iron. The main components of plant biomass are fibre or cell wall components (carbohydrates [mainly cellulose or hemicellulose fibres which impart strength to the plant structure], lignin [holds the fibres together], ash [inorganic component of biomass] and extractives) (Basu, 2010).

Plant biomass can roughly be divided into food supplies (rich in starch, fat and protein), which account for less than 20% by mass of the total global biomass, and lignocellulosic, non-food biomass (trees, grasses, agricultural residues), that make up more than 80% of the total biomass. Lignocellulosic biomass (average elemental composition $CH_{1.4}O_{0.6}$) consists of cellulose (with 38-50% by mass, the most abundant form of carbon in the biosphere), hemicellulose (23-32%), lignin (15-25%), and extractives (1-5%) (Czernik, 2008). The carbon content of lignin is 64%, and is substantially higher when compared to the carbon content of cellulose (42%) (Kaltschmitt et al., 2009). Lignocellulosic, non-food biomass also includes the products, by-products, residues and waste from agriculture, forestry and related industries, as well as the non-fossilized and biodegradable organic fraction of industrial and municipal wastes (UNFCCC, 2005). Wastes are secondary biomass, as they are derived from primary biomass during different stages of their production or use. Municipal solid waste is an important source of waste biomass and much of it comes from food scraps, lawn clippings, leaves and papers.

In general, biomass (including organic wastes from agriculture, forestry and urban dwellings) as a fuel suffers from its bulky, fibrous, high moisture content and low-energy-density nature, leading to key issues, including high transport cost and poor grindability (Abdulllah and Wu, 2009). Thus, further processing, i.e., shredding, densification and shaping (e.g., briquetting), and carbonization are needed to transform the various types of organic waste into an acceptable form of domestic fuel (Vest, 2003). Feed particle size can significantly affect the balance between char and liquid yields. Larger particle sizes tend to give more char by restricting the rate of disengagement of the primary vapour products from the hot char particles, therefore increasing the scope for secondary char-forming reactions (discussed in Section 2.3.4) (Antal and Grønli, 2003). Domestic fuel produced from organic waste should generally be homogeneous, compact, dry, and of high carbon content. The suitability of each type of biomass as feedstock for pyrolysis is dependent on its nature and chemical composition, as well as on environmental, economic and logistical factors.

- **Criteria for assessing biowaste suitability for char production**

To assess the suitability of biowaste types for slow pyrolysis, two groups of criteria need to be considered (Chardust and Spectrum Technical Services, 2004; Faraji et al., 2014; Rweyemamu, 2014):

1) Availability and accessibility aspects

- Total amount generated
- Annual/seasonal variation
- Pre-existing and competing uses
- Cost of waste
- Degree of centralization

While total quantities of waste generated is important to estimate the theoretically available substrate for pyrolysis and further processing, such as briquetting, annual/seasonal variation in supply is the measure of how consistent a particular biowaste type is available. Reliable and consistent supply of a particular biowaste type to a production facility is a key requirement to achieving efficiency and effectiveness in commercial scale fuel production. High demand for a particular biowaste type by competing uses negatively affects its accessibility. The degree of centralization describes the amount of biowaste per area, which affects the transportation costs, as sparsely distributed wastes in small quantities need to be brought to the char production site first, causing additional costs.

2) Physical-chemical properties

- Bulk density
- Particle size and uniformity
- Moisture content
- Fixed carbon content
- Ash content

Bulk density (kg/m^3) is relevant for calculating transportation costs and the pyrolysis unit size and loading rate, whereas particle size and uniformity is needed to understand if a size-reduction or homogenization step (e.g., crushing, milling etc.) is required prior to carbonization. Moisture content is an important parameter as most pyrolysis units work best using a feedstock with moisture content in the range of <20% (Cummer and Brown, 2002). Freshly harvested biomass can have a moisture content of up to 70% and requires a significant amount of energy input for drying. Fixed carbon content provides an approximation of the theoretically possible char yield, while ash content includes the inorganic components that reduce the heating value per product volume and weight. Feedstock with high ash content (e.g., rice husks) or which are contaminated with inert material (e.g., sand) produce char with ash content that is proportionally high to mass yield, which drastically lowers the heating value of the char. The heating value of the raw biowaste does not provide highly useful information, as the differences are levelled through the carbonization process, i.e., all charred biowaste after pyrolysis show similar higher heating values of approximately 25 MJ/kg dry matter. In comparison, the higher heating value of wood charcoal is 31–33 MJ/kg and of char briquettes 22–29 MJ/kg, which is a bit lower due to the binding material used (Mwampamba et al., 2012).

4.2 Slow pyrolysis conversion process

Biomass is heated in the absence of oxygen, or partially combusted with a limited oxygen supply, to produce a carbon-rich solid residue, an oil-like liquid, and a hydrocarbon-rich gas mixture (Demirbas, 2001). Heating releases the biomass' volatile compounds, resulting in a lightweight combustible fuel mixture of gases and vapours. Charcoal has a higher heating value of about 28 MJ/kg, depending on the total carbon content (Baker, 1983 in Maes and Verbist, 2012). Slow pyrolysis refers to process conditions with slow heating rates (typically 5–80°C/min) coupled with moderate temperatures (typically 300–600°C), which maximize the char yield. Such process conditions can be easily achieved in furnaces with various scales and shapes, such as fixed beds and rotary kilns, although achieving the theoretical limit of char yield requires a well-designed reactor to maximize the residence time for organic vapours (Antal and Grønli,

2003). At relatively low temperatures of approximately 300°C, a high yield of charcoal is obtained. This charcoal has a high content of volatile material, which is undesirable because it produces noxious fumes during use. Temperatures around 600°C give lower charcoal yields, but the lower content of volatiles in the charcoal makes it a preferred fuel (Seidel, 2008).

The decomposition mechanism of most biomass types into solid, liquid and gaseous fractions is still unknown because of the complexity of pyrolysis and differences in biomass composition (Burhenne et al., 2013). Conversion characteristics can be grouped into thermochemical (ash and volatile yields, reactivity of volatile products, etc.), intra-particle rate (thermal properties, moisture content, size, kinetics and energetics of chemical processes, etc.) and extra-particle rate (heat transfer from reactor to particle, residence time and mass transfer conditions dependent in turn on the type of conversion unit) (Kanury, 1994). There is a further classification of intra-particle rate characteristics into two main categories: those related to feedstock preparation, such as particle size and moisture content, and the intrinsic physical and chemical properties (Babu, 2008).

Figure 6 illustrates the changes in weight, volume and heating value after slow pyrolysis of wood to charcoal.

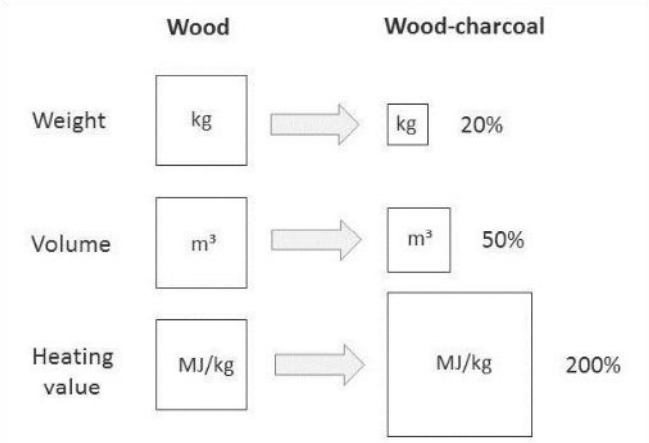


Figure 6: Properties of wood in comparison with wood-based charcoal due to carbonization (Kaltschmitt et al., 2009)

Since the carbon content of charcoal approaches an asymptote with increasing peak temperature, the limiting asymptotic value is an important property of the material and can be analysed by means of proximate analysis (Moisture: ASTM E871; Volatile Matter: ASTM E872; Ash: ASTM D1102). If chemical equilibrium is attained in the kiln, the fixed-carbon yield should approximate the theoretical carbon yield that results from a thermochemical equilibrium calculation (Antal and Grønli, 2003).

4.2.1 Physical-chemical process

The actual reaction scheme of pyrolysis of biomass is extremely complex because of the formation of over a hundred intermediate products (Babu, 2008). Pyrolysis of biomass is, therefore, generally modelled on the basis of apparent kinetics. Ideally, the chemical kinetics model should account for the primary decomposition reactions, as well as the secondary reactions. Significant contributions have been made on kinetic modelling (Roberts, 1970; Bradbury et al., 1979; Pyle and Zaror, 1984; Nunn et al., 1985; Matsui et al., 1987; Wang and Kinoshita, 1993; Jalan and Srivastava, 1999; all in Babu and Chaurasia, 2003). Koufopanos et al. (1991) proposed a two-step mechanism scheme for describing the kinetics of the pyrolysis of biomass: this model indicates that the biomass decomposes to volatiles, gases and char. The volatiles and gases may further react with char to produce different types of volatiles, gases and char when the compositions are different. Therefore, the primary pyrolysis products participate in secondary interactions, resulting in a modified final product distribution (Babu and Chaurasia, 2003). In other words, primary char is formed directly from the solid-phase biomass carbon atoms. Secondary char is formed from volatiles that redeposit within the structures of the initial primary char (Taylor, 2010).

According to Babu and Chaurasia (2003), the complex reaction mechanisms of biomass pyrolysis can be described in a simplified way:

I.	Biomass → Water + Unreacted residue	→ Moisture and some volatile losses
II.	Unreacted residue → $(Volatile + Gases)_1 + (Char)_1$	→ Occurrence (fast) and chemical re-arrangements (slow) of primary char
III.	$(Char)_1$ → $(Volatile + Gases)_2 + (Char)_2$	→ Char decomposes at a very slow rate and carbon-rich residual solid is formed

Traditional charcoal-making is also described in three successive stages that can be characterized by the colour of smoke emitted: drying (white smoke), pyrolysis (yellow smoke) and process completion at char combustion (blue smoke) (Brown, 2009).

The carbonization process of small biomass particles is often divided into four stages (Kaltschmitt et al., 2009; Payakkawan et al., 2014):

1. Biomass is heated to **180-220°C** at which the water inside the gaps between cells (free water) and at the cell boundary (bound water) is completely removed and small concentrations of CO_2, acetic acid and formic acid are driven out. This is an endothermic process (i.e., it requires energy input). Due to the high enthalpy of evaporation of water, much of the heat required for the process of thermal degradation is absorbed during the drying process, thus further temperature increase of the biomass is slowed until the drying is finished. The organic mass mainly remains at this stage, and decomposition occurs only at higher temperatures when water has been driven out of the biomass. It is necessary that the water content of the biomass is below a certain percentage (<50-60% by mass) so that the pyrolysis process evolution continues. The stage of heating and drying can also be illustrated by the thermogravimetric curve, which shows the reduction of mass of a wooden sample as a function of temperature (Kaltschmitt et al., 2009).

2. Between **220 and 280°C** pyrolytic degradation begins and volatiles are released, emitting more CO_2, acetic acid and formic acid. Once the temperature reaches 280°C, hemicelluloses are fully decomposed. The temperature is maintained at 280°C for an extended period of time for an optimal carbonization process, whereby the heat is evenly distributed throughout the biomass inside the reactor. The yield from this stage is of pale grey colour, consisting of CO, CO_2, acetic acid, and methanol. At this stage, the reactions are still endothermic and almost all products are non-flammable.

3. From **280 to 400°C** biomass self-decomposes through strong exothermic reaction, causing a rise in the temperature due to heat release (ca. 880 kJ/kg wood substance; Kaltschmitt et al., 2009). This results in the formation of highly flammable gases, mainly carbon monoxide (CO), methane (CH_4), formaldehyde (CH_3OH), acetic acid ($C_2H_4O_2$) and formic acid (CH_2O_2), as well as methanol (CH_2O) and hydrogen (H_2). They are driven out so fast from the solid particle matrix that the gas stream pulls with it tiny drops of condensable organic compounds, which occur as visible smoke. Celluloses in the biomass rapidly decompose at 280°C and their yield is of white and yellow vapour with pungent smells and yields high quality wood vinegar if condensed. What remains is char that keeps its fibrillar wood structure until approximately 300°C. Lignin decomposes at approximate temperatures of 310–400°C. Above 400°C, biomass is entirely converted into charcoal and the crystalline structure of graphite is formed. From this point onwards, the reactions are endothermic again.

4. **Above 500°C**, the initial biomass is almost totally degraded and the gases driven out from it are further broken down during their passage through the already charred layers, thereby, forming inflammable gases, such as CO and H_2 (char serves as a catalyst for secondary reactions). Although biomass becomes charcoal after approximately 400°C, a high quantity of tar remains. Tar causes the charcoal to be of low quality and, once burned, is emitted as benzopyrene and dibenzanthracene, both of which are carcinogenic. Therefore, charcoal quality is improved at this final stage by drying it at 500-600°C for a period of time to remove tar (Payakkawan et al., 2014).

It has to be noted that there is a difference between the physical phenomena of decomposition/pyrolysis of large and small biomass particles. The reaction processes as described above apply to small particles <0.3mm, where it can be assumed that every point in the particle achieve the surrounding temperature immediately (isothermal) and it undergoes the same physical and chemical processes simultaneously during pyrolysis. When dealing with large biomass particles a temperature gradient is established, and the outer part can be pyrolyzing while the inside is still at room temperature. This can result in no clear observed transition between drying (white smoke) and pyrolysis (brown/blue smoke). Depending on the carbonization system and feedstock packing, the whole mass (although comprised of many small particles) in an immobile reactor can show behaviour identical to the pyrolysis of one large particle.

Both heat transfer and chemical reactions vary with the biomass composition since the three polymeric constituents, namely lignin, cellulose and hemicellulose, have different internal energy and heating values (Bayerbach, 2006; in Burhenne et al., 2013). As a result, they differ markedly in their thermal stability with lignin being the most stable of all structural components.
Figure 7 reveals how the different components of biomass degrade at different temperatures. It can be seen that wooden charcoal primarily consists of lignin, as it is only degraded to approximately 60% through pyrolytic decomposition (Kaltschmitt et al., 2009). According to Yang et al. (2006), lignin does not decompose completely until temperatures up to 700°C are reached. It was also found that pyrolysis of woody biomass with high lignin content is an endothermic reaction, whereas pyrolysis of herbaceous biomass, with lower lignin content, involves an exothermic reaction (Yang et al., 2006), but the overall process remains endothermic.

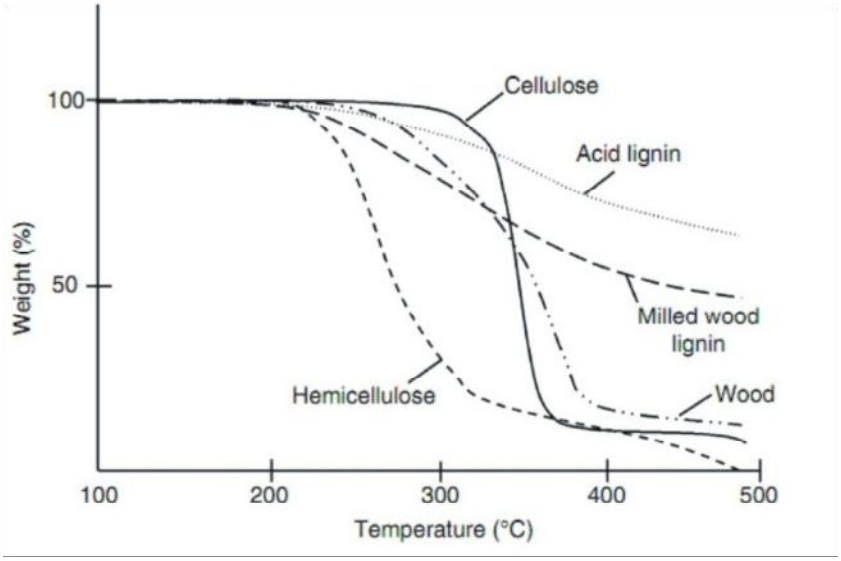


Figure 7: Weight loss of wood and its components cellulose, hemicellulose and lignin as a function of temperature (http://jfe-project.blogspot.com/2012_03_01_archive.html; see also Kaltschmitt et al., 2009)

William and Besler (1996; in Brown, 2009) reports that at very low heating rates typical of muffle furnaces or traditional charcoal kilns, cellulose decomposition begins at temperatures as low as 250°C. Shafizadeh (1985) describes the decomposition of hemicellulose at 225–325°C, cellulose at 325–375°C, whereas lignin decomposes gradually over the temperature range of 250–500°C.

Until now, no coherent picture about the pyrolytic degradation mechanisms of different components, such as lignin, cellulose and hemicellulose, exists. Much is known, however, about the thermal degradation of cellulose as it represents the most important component of wooden substances and its chemical complexity is low compared to other components (Kaltschmitt et al., 2009). Thus, cellulose serves as a representative model compound for carbonization. The stoichiometric equation for the production of charcoal can be written as (Antal and Grønli, 2003):

$$C_6H_{10}O_5 \rightarrow 3.74C + 2.65H_2O + 1.17CO_2 + 1.08CH_4 \quad (4)$$

The basic phenomena that take place during pyrolysis of a dry biomass are the following (Babu and Chaurasia, 2003):

1) Heat transfer from a heat source, leading to an increase in temperature inside the fuel
2) Initiation of pyrolysis reactions due to the increased temperature, leading to the release of volatiles and the formation of char
3) Outflow of volatiles through char; partial pressure-related inflow of some volatile gases resulting in heat transfer between the hot volatiles and cooler unpyrolyzed fuel
4) Condensation of some of the volatiles in the cooler parts of the fuel to produce tar
5) Autocatalytic secondary pyrolysis reactions due to these interactions

Thermodynamic equilibrium calculations show that the char yield of most biomass may not exceed 35% (Basu, 2010). Charcoal contains both primary charcoal and secondary charcoal, the latter is a product derived from the decomposition of the organic vapours (tars) onto the solid carbonaceous solid. This decomposition is probably catalysed by the charcoal (Cookson, 1980; Xu et al., 1996; Radovic and Sudhakar, 1997; Brandt et al., 2000; all in Antal and Grønli, 2003). While Chen et al. (1997) remarked that secondary charcoal is as reactive as primary charcoal. Demirbas (2004) stated that the formation of secondary charring makes the char less reactive. Low gas flows provide increased opportunities for reactive volatile matter to interact with the solid carbonaceous residue of pyrolysis and produces more charcoal. Overall, little knowledge of the kinetics of secondary char formation exists (Antal and Grønli, 2003).

Figure 8 presents an overview of the biomass pyrolysis pathway, indicating primary, secondary and tertiary processes, the products of the solid, liquid and vapour phase for high and low pressure processes.

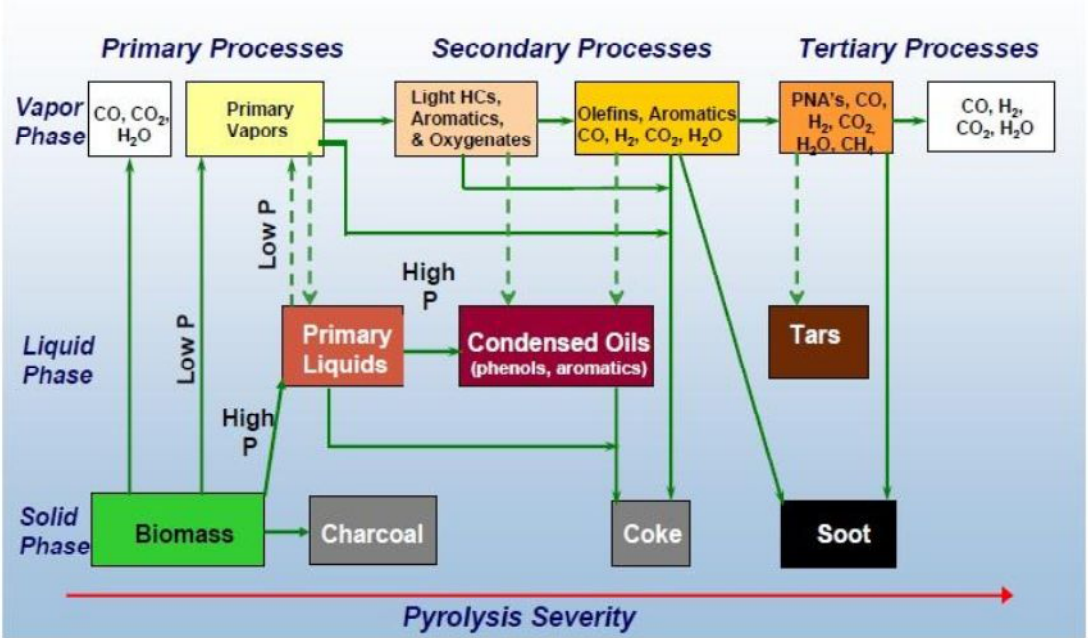


Figure 8: Biomass pyrolysis pathways (Evans and Milne, 1987; in Czernik, 2008)

As a side-note: ashes from biomass combustion contain considerable amounts of plant nutrients, which create an opportunity for its use as an amendment to agricultural or forest soils. It was reported that during the pyrolysis of biomass, potassium (K), chlorine (Cl) and nitrogen (N) vaporize at relatively low temperatures, while calcium (Ca), magnesium (Mg), phosphorus (P) and sulphur (S) vaporize at considerably high temperatures due to increased stability. Slow biomass pyrolysis is reported to result in high quantities of K, Cl, Si, Mg, P and S in biochar (Amonette and Joseph, 2009; in Duku et al., 2012).

4.2.2 Operational parameters and control

Numerous factors affect the pyrolysis rate and the yields, composition and properties of the products. It is generally accepted that the process parameters that have the major influence on the products are pyrolysis temperature, heating rate and pressure (Beis et al., 2001; Babu and Chaurasia, 2003; Bridgewater,

2003; Goyal et al., 2008; Neves et al., 2011). In addition, particle size, shape and properties (chemical composition, ash content, density, moisture content, etc.) also play an important role (Di Blasi, 2008).

To achieve good yields of high quality products, reaction conditions must be well controlled. Heat must be sufficient to dry the biowaste and maintain a temperature for efficient carbonization. The temperature in the reactor is the most important operational control variable for pyrolysis processes (Toole et al., 1961; Brownsort, 2009). Two ways to control the heat conditions of pyrolysis reactors are: i) to observe the colour of vapours produced, and ii) to measure and control the temperature inside the reactor either manually or using standard feedback control systems (Garcia-Perez et al., 2011).

Control by observation of vapour colour is an approach typically used with low-cost carbonization reactors without heat or bio-oil recovery. The production of steam results in white smoke, indicating the drying of biomass (Picture 1), whereas a yellow/brown smoke is typically associated with pyrolysis (Picture 2). As pyrolysis continues, the smoke becomes more and more transparent and finally turns bluish when char begins to combust (Picture 33). Once the carbonization process is complete, the cooling cycle begins by sealing all ports. Another control method is by direct temperature measurement to monitor both the time and temperature of the carbonization process (Toole et al., 1961). Although it is safe to open the reactors and discharge the char once the temperature is lower than 65°C (Emrich, 1985), the reactor should be checked for localized hot spots before discharging begins (Garcia-Perez et al., 2011).



Picture 1: Pyrolysis vapors exiting an ARTI-style drum kiln (photo: D. Sweeney)



Picture 2: Pyrolysis vapors from an ARTI-style drum kiln (photo: D. Sweeney)



Picture 3: Clear blue smoke from an ARTI-style kiln indicating char combustion (photo: D. Sweeney)

Material flow rates, both solid and gas phase, particle size and moisture content of feedstock, together with the reactor temperature, control the key parameters of heating rate, peak temperature, residence time of solids and contact time between solid and gas phases. These factors affect the product distribution and the product properties. Gas flow rate through the reactor affects the contact time between primary vapours and hot char and, therefore, affects the degree of secondary char formation. Low flows favour char yield and are preferable for slow pyrolysis. Pressure has a similar effect. Higher pressure inhibits the escape of volatiles, increases the vapour pressure of tar species, and increases the reactivity of vapours within and at the surfaces of char particles, so increasing secondary char formation. The effect is most marked at pressures up to 0.5 MPa (Brownsort, 2009). For pyrolysis under pressure, moisture in the vapour phase can systematically increase the yield of char. This is believed to be due to an autocatalytic effect of water, hence, reducing the activation energy for pyrolysis reactions.

The thermodynamics of pyrolysis are also influenced by the gas environment. The reaction is less endothermic at higher pressures and low gas flow rates. This is rationalized as being due to the greater degree of secondary char-forming reaction that occurs. Hence, higher char yields are associated with conditions where pyrolysis is exothermic; such conditions will favour the overall energy balance of processes targeting char as a product. In summary, any factor of pyrolysis conditions that increases the contact between primary vapours and hot char, including high pressure, low gas flow, large particles or slow heating is likely to favour char formation at the expense of liquid yield (Brownsort, 2009). Antal and Grønli (2003) provide data from their own work, indicating that char formed under low flow, high pressure conditions with consequent higher char yields, also have higher fixed-carbon yields.

Antal et al. (1996) explored the influences of thermal pre-treatments, heating rate, peak temperature, catalysts, feedstock composition, and other conditions on charcoal yields, where they found elevated pressure combined with a prolonged vapour phase residence time to significantly increases the yield:. Carbonization at elevated pressure improves the yield of charcoal from biomass particles because under pressure, the tar-laden pyrolytic vapours have a smaller specific volume; consequently, their residence time within the particle and in the near vicinity of the particle increases. Also, the partial pressure of the tarry vapour within and in the vicinity of the particle is higher. These effects are magnified when the flow of gas through the particle bed is small. The tarry vapour is composed of a complex reactive mixture of organic compounds including vapour phase sugars and anhydrosugars, and their oligomers, fragments of sugars, and lignin moieties-that are highly unstable at elevated temperatures. These tarry vapours rapidly decompose on the surface of charcoal, producing secondary charcoal and a gas composed primarily of water, carbon dioxide, methane, hydrogen, and carbon monoxide. At elevated pressure, an increase in the moisture content of the feed increases the yield of charcoal produced by an externally heated retort. There is some evidence that moisture acts as a catalytic agent for the formation of charcoal (Antal and Grønli, 2003). Mok and Antal (1983) suggested that pressure is a kinetic rather than a thermodynamic effect: high pressures prolongs the intra-particle residence time of pyrolyzing vapours, as well as increases the rate of decomposition reactions that allow a closer approach to the expectations of thermodynamic equilibrium (Brown, 2009).

4.2.3 Heating methods

There are different methods of heating to initiate pyrolysis and maintain high temperatures during carbonization. These methods apply heat on the biomass and also vary as to whether oxygen is present (oxic pyrolysis) or oxygen is absent (anoxic pyrolysis). The energy required to drive the process can be supplied either: (i) directly as the heat of reaction, (ii) directly by flue gases from combustion of by-products and/or feedstock, (iii) indirectly by flue gases through the reactor wall, or (iv) indirectly by heat carrier other than flue gases (e.g., sand, metal spheres, etc.) (Duku et al. 2012).

The first three methods of heating are considered relevant for low-tech or small-scale production of char (Taylor, 2010; Garcia-Perez et al., 2011) and are, therefore, described in more detail:

I. **Oxic pyrolysis by partial combustion (autothermal systems)**

Part of the raw material in the reactor is combusted with controlled entry of air to create hot gases which pass through and heat the remaining biomass, providing the energy necessary for the process (see
Figure 9). By combusting a portion of the biomass, the yield of char is reduced. Therefore, it is best to operate these systems in areas where raw materials are cheap. To preserve the created charcoal, air must be limited, which results in emissions of products of incomplete combustion (PIC), including methane and other hydrocarbons with large greenhouse gas (GHG) potential. Many of these PICs condense as soon as they exit the kiln, creating copious visible smoke. Nevertheless, this is the method by which most fuel charcoal is made in developing countries. Without proper control and expertise in this production method, it can be very inefficient, with yields as low as 5%. It is essentially the method of a controlled open fire, traditional earth mound kiln or masonry or metal kilns with often poor control of temperature within the reaction space, both in regard to uniformity and duration of treatment. These systems typically have low capital costs partly because no heat surfaces are needed and condensable products are usually not recovered.

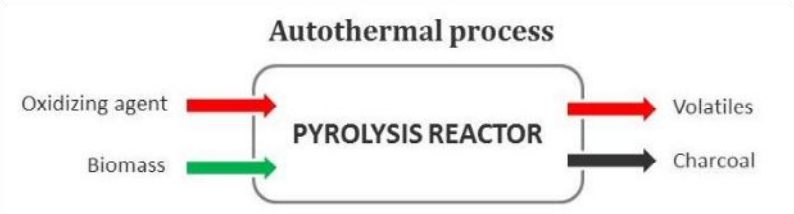


Figure 9: Autothermal heating pyrolysis system (Fournier, 2009; in Garcia-Perez et al. 2011)

Top-Lit Up-Draft (TLUD) gasifier stove is a cookstove technology that produces heat for cooking by burning synthesis gas from the gasification of biomass with production of char (Roth, 2011). Depending on the design and operating conditions, the char produced can continue to gasify or can oxidize with more primary air to continue produce heat for cooking or can be quenched and collected as solid char. Most researchers and pioneers of TLUD stoves advocate the use of char for soil amendment. TLUT gasifier stoves burn relatively cleanly because the biomass is lit from above and the pyrolysis gases, formed in a space of limited air, are allowed to rise away from the biomass to a region where sufficient secondary air is admitted, resulting in their complete combustion. TLUD devices only operate properly on feedstock that has been processed into uniform, small size pieces.

II. Anoxic pyrolysis by indirect heating

With indirect heating, the retort is heated from the outside and no air enters the reactor. Biomass is placed in a container and external heat source transmits the heat necessary for pyrolysis through its walls (see Figure 10). The transmitted heat dries the biomass and raises its temperature to the point where pyrolysis starts. When pyrolysis gases are emitted, they exit into a combustion zone outside the retort, where they can be burned completely with sufficient air and the heat generated can be used to maintain the pyrolysis process in the kiln. In an efficient system only a portion of the available heat is needed to drive the pyrolysis, leaving excess heat to dry feedstock or initiate further pyrolysis or be harnessed for other purposes. This method is suitable for the recovery of volatiles and yields large amounts of char, low emissions, and more control of the process (Toole et al., 1961; in Garcia-Perez et al., 2011). It results in higher yield and more control over the process and emissions compared to traditional methods. In this method all heat required for pyrolysis is transferred through the reactor walls. Since the heat transfer inside the biomass bed is relatively slow, large reactors cannot depend solely on this heating method, but need to be accompanied by the use of internal heat addition.

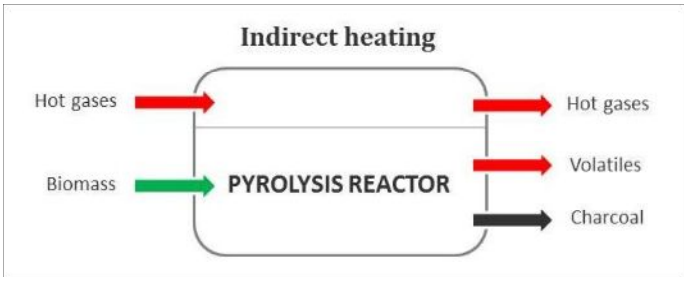


Figure 10: Indirect heating pyrolysis system (Fournier, 2009; in Garcia-Perez et al. 2011)

III. Carbonization by contact with hot gases (direct heating with inert gas)

As the size of the retort increases, retort designs suffer increasing problems of poor heat transfer, and, thus, slow char making. Both raw biomass and charcoal are good insulators; therefore, it can take hours or days for the externally applied heat to fully pyrolyze the interior of the retort. This problem can be overcome by circulating hot gases which are oxygen-free through the retort (see Figure 11). Direct contact of hot gases with feedstock can significantly increase the heat transfer rate to the material. Pyrolysis gases can be combusted and recirculated as hot gases. The challenge will be the dilution of the flammable pyrolysis gases with CO_2 and H_2O from the recirculated gases. The amount of combustion gases, which are fed back through the reactor bed, must be controlled and limited to maintain gas flammability (Taylor, 2010). Fuel is used to heat the heat carrier. Typically, wood of infe-

rior quality or leaves, can be combusted in a separate combustion chamber to provide heat. Char and byproduct yields are high, and this system is suitable for medium- to large-scale production (Garcia-Perez et al., 2011).

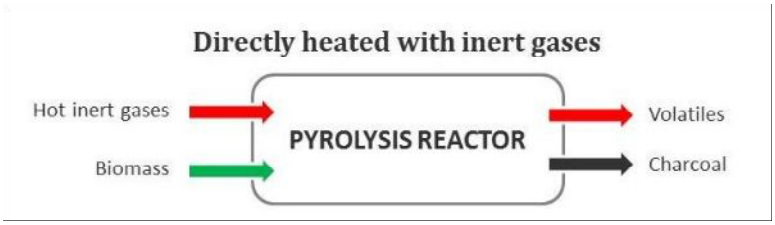


Figure 11: Pyrolysis system with direct heating with inert gases (Fournier, 2009; in Garcia-Perez et al., 2011)

The heat generated by pyrolysis is proportional to the amount of charcoal produced by the primary and secondary carbonization reactions. When the yield of charcoal is high, the pyrolysis chemistry is strongly exothermic. If the feedstock is dry and has properties that would generate high char yield, the exothermic evolution of the process can elevate the temperature of the incoming feedstock sufficiently to initiate carbonization reactions (Antal and Grønli, 2003). Several studies (Arseneau, 1971; Mok and Antal, 1983; Milosavljevic et al., 1996; Rath et al., 2003) clearly show that exothermicity in biomass pyrolysis is associated with the formation of char (Di Blasi, 2008).

4.3 Overview of existing slow pyrolysis technologies

While properties of the carbonaceous feedstock are important to determine the quantity and quality of charcoal that can be produced, the pyrolysis technology is also an important factor. Until the beginning of the 20th century, nearly all charcoal was produced using traditional methods. Typically, an earthen pit, also known as an *earth pit kiln,* is filled with wood, then ignited and covered with earth. Another method was to use a pile of wood that was ignited and covered with soil; this is known as an *earth mound kiln*. Carefully placed openings in the earthen mound allow gaseous and aerosol pyrolysis products to exit and allow air to enter and enhance combustion and heat generation. These technologies are low-cost, simple to construct, scalable, and can be applied nearly anywhere in a profitable way, accounting for their continued and widespread use. However, they are relatively inefficient, with charcoal yields of less than 15%, and the charcoal produced is of inconsistent quality. This derives from the setup and the difficulty to control the process. Additionally, there is a high level of harmful emissions released, causing environmental pollution.

During the 1970s and 1980s, efforts were made to improve traditional wood pyrolysis technologies by adding chimneys to earthen kilns, as in the case of the Casamance kiln. Steel kilns (e.g., D-Lab, ARTI and portable ring kilns) and brick kilns (e.g., Brazilian beehive) were also used for small-scale charcoal production. Such improvements, as well as improved control of air entry into the kiln and less supervision and labour, led to increased charcoal yields with up to 25% conversion efficiency. However, all technologies continue to rely on partial oxidation of input wood to provide energy for pyrolysis and depend on wood moisture content and level of operator experience. In addition, equipment and maintenance costs inhibit access to these technologies to small-scale, traditional producers. Recent developments utilize low-cost, improved small-scale pyrolysis technologies for production of charcoal from non-woody biomass and residues (e.g., urban organic waste and agricultural residues). Some examples of technologies for these applications include: drum-style kilns, such as the ARTI and D-Lab kilns among others, and retorts like the hornito and Adam retort, also known as the Improved Charcoal Production System (ICPS).

During the 20th century, industrial demand for charcoal in Europe and North and South America resulted in the development of larger-scale metal and brick, batch-operated and continuous retort kilns. These technologies resulted in conversion efficiencies of 20-25% and greatly improved charcoal consistency and quality. However, the problem of harmful emissions persisted, which, along with the increased availability of low-cost fossil fuel alternatives, resulted in the reduction of charcoal production in these regions.

Current industrial charcoal production technologies utilize heat-resistant steel and ceramic brick designs that can withstand the high-temperature reactor environment. Dry wood is subject to temperatures up to 900°C, which results in the rapid release of gaseous and aerosol products. Heat is recovered from these products and used to provide energy to maintain the high reactor temperature and to pre-dry incoming wood, greatly increasing conversion efficiencies (25-30%) and product quality (high fixed carbon content), and reducing harmful carbon monoxide and tars. These technologies are common in developed countries and some developing countries (e.g., China, Ghana and South Africa), but are inaccessible to many non-industrialized countries. In many cases these technologies were developed by charcoal producers and are, therefore, not commercially available (FAO, 2008).

In general, pyrolysis technologies discussed can be classified in terms of their reactor type, operation type (batch or continuous), scale, construction material, conversion efficiency, emissions, and auxiliary requirements among other characteristics. A summary of technology classifications and examples is presented in Table 8.

Table 8: Classification and important characteristics of carbonization technologies

Reactor type	Process type	Capacity	Construction materials	Conversion efficiency (mass%)	Energy source	Residence time	Emissions	Fixed Carbon (mass%)	Auxiliary requirements	Portability & permanence	Working life	Capital Cost	Reference(s)
EARTHEN													
Earth pit, mound	Batch	50-32,000 kg[1], 3-100 m3, 180-330 m3[2]	Soil, sod	<15, 22-35[1], 90 kg charcoal /m3 wood[2], 20[3], 15-16 (oven dry)[4], 27[5]	Partial oxidation	5[1]-20 days, 20 days / 180 m3[2], 14-24 days[4]	CO_2: 1058-3027 g/kg charcoal CO: 143-333 g /kg charcoal CH_4: 32-62 g /kg charcoal TSP: 13-41 g /kg charcoal[1]	70-80, 75[1], 71-78[6]	None	Impermanent	n/a	$27/ton charcoal[3]	FAO 1983, Stassen 2002, Girard 2002, Noble 2011, [1]Pennise et al 2001, [2]USFS 1961, [3]Ando et al 2004, [4]Nturanabo et al 2011, [5]KEFRI 2006, [6]Smith et al 1999
Casamance, Kasisira, Bus kiln	Batch	50-1000 kg, 60-130 m3[1]	Soil, sod, sheet metal/drum	15-31[3], 100 kg / m3 wood[1], 30 (oven dry)[4]	Partial oxidation	5 days[1], 6-8 days[4]	n/a	80-90[2]	None	Impermanent	n/a	$200	[1]Karch et al 1987, [2]Girard 2002, [3]Stassen 2002, [4]Nturanabo et al 2011, KEFRI 2006
BRICK													
Brazilian Beehive	Batch	20 t wood[1], 8-50 m3, 180-330 m3[2]	Brick, mortar	13-35, 29[1], 90 kg charcoal /m3 wood[2]	Partial oxidation	2[1]-10 days, 20-30 days / 270 m3[2]	CO_2: 1533 g/kg charcoal CO: 373 g /kg charcoal CH_4: 57 g /kg charcoal[1]	75[1]-90	None	Stationary	n/a	$150-1500[3]	Simmons 1963, FAO 1983, Stassen 2002, Noble 2011, Stewart 1984, [1]Pennise et al 2001, [2]USFS 1961, [3]Kristofferson 1986, Smith et al 1999
Argentine Half Orange	Batch	30 t wood	Brick, mortar	27	Partial oxidation	13-14 days	n/a	n/a	None	Stationary	n/a	n/a	FAO 1983
METAL													
Missouri	Batch	80 t wood[2]; 300 tpy charcoal[3], 350 m3[4]	Steel, brick/ concrete	5-20[1] 36[2], 25-33[4]	Partial oxidation	80 hrs[2]	CO_2: 543[2]-560[3] g/kg charcoal CO: 140[3]-162[2] g /kg charcoal CH_4: 37[2]-54[3] g /kg charcoal TSP: 160 g /kg charcoal[3]	92[2]	Tar recovery[2]	Stationary	n/a	$15000[4]	Simmons 1963, [1]FAO 2008, [2]Pennise et al 2001, [3]EPA 1995, [4]Kristofferson 1986

Reactor type	Process type	Capacity	Construc-tion mate-rials	Conversion efficiency (mass%)	Energy source	Residence time	Emissions	Fixed Carbon (mass%)	Auxiliary require-ments	Portabil-ity/perma nence	Work-ing life	Capital Cost	Reference(s)
Mark V	Batch	300-400 kg wood[1]	Steel	20-25[1], 30-31[2]	Partial oxidation	23-42 hrs[2], 38 hrs[3]	N/A	70[3]	None	Portable	n/a	$2000-5000[1]	[1]Kristofferson 1986, [2]Stewart 1984, [3]Killmann 1996
Chimney kiln	Batch	4-14 m3	Sheet met-al & iron beams	0.3-0.4 m^3 charcoal /m^3 wood	Partial oxidation	52-84 hrs	n/a	n/a	None	Portable	n/a	N/A	Olsen & Hicock 1941
DRUM													
Vertical (D-Lab, ARTI, Kinyanjui)	Batch	200 L, 12-15 kg biomass[4]	Mild steel	13-30, 21[2], 19[3], 23-28[4]	Partial oxidation	0.5-4 hours, 1 day[2]	CO_2: 1517 g/kg charcoal CO: 336 g /kg charcoal CH_4: 57.7 g /kg charcoal TSP: 4.2 g /kg charcoal[5]	77-83[5]	None	Portable	0.5-2 years	$13-17[1], $61/ton charcoal[2]	FAO 1983, [1]D-Lab, Rao 1984, Stewart 1984, [2]Ando et al 2004, [3]Karch et al 1987, [4]Kristofferson 1986, [5]Smith et al 1999
Horizontal (KEFRI)	Batch	200 L	Mild steel	24[1], 28-30 (bamboo)[2]	Partial oxidation	6-12 hrs[2]	n/a	n/a	None	Portable	0.5-2 years	$13-17	[1]Stewart 1984, [2]KEFRI 2006
Large drum, Mark V, TPI, Black Rock Forest, Ring, New Hamp-shire	Batch	7 m3, 2-5 m3[1], 100-150 tpy	Mild steel	20-30	Partial oxidation	1-4 days	20-45% CO_2, 31-34% CO, 12-16% CH_4	n/a	None	Portable	2-3 years	$600-1000	FAO 1983, Noble 2011, Stewart 1984, Levy 1995, [1]USFS 1961, KEFRI 2006
Horizontal rotary	Continu-ous	<1 tph - 100 tpd	Steel com-ponents and/or refractory interior	n/a	Partial oxidation or retort	n/a	n/a	n/a	Electricity (motor drive and/or indi-rect heat), mechanical feeder, external combustor and exhaust recycle	Stationary	n/a	n/a	Duku et al 2011

Reactor type	Process type	Capacity	Construction materials	Conv. eff. (mass%)	Energy source	Residence time	Emissions	Fixed C (mass%)	Auxiliary requirements	Portability & permanence	Working life	Capital Cost	Reference(s)
RETORT													
Adam	Batch	3 m3, 750 kg wood (wet)	Brick or earth blocks	30-42 (dry basis)	Partial oxidation & volatile combustion	12 hrs	n/a	n/a	None	Stationary	n/a	€300	Adam 2009
Carbo Twin Retort	Batch	900 tpy (hardwood), 2 x 5m3[1]	Steel	30-33[2]	Ext. heat & volatile combustion	32-36 hrs (includes cooling)[1]	complies w/ Dutch emission standards	n/a	Oil burner, fork lift, hoist and rail, sand lock, EGR	Stationary	n/a	€1 million+[1]	[1]FAO 2008, [2]Rautiainen et al 2012
Wagon, Arkansas retort	Batch	6000 tpy (wood)	Steel	n/a	Volatile combustion	25-35 hrs (includes cooling)	n/a	n/a	Rail & car system w/ mechanical drive; exhaust gas & heat exchange piping; external combustion chamber	Stationary	n/a	High maintenance & operating cost	FAO 2008
Calusco Tunnel Retort		6000 tpy	High-temp. steel	n/a	Volatile comb.	25-35 hrs	n/a	n/a	n/a	Stationary	n/a	High	FAO 2008
Lambiotte, SIFIC, CISR	Continuous	≤12500 tpy (oak wood)[1], 3000-20000 tpy[3]	Steel	30-35[2,3]	Volatile combustion	n/a	n/a	n/a	lock-hopper; Closed gas loop piping; condensers & scrubbers (SIFIC), ext. combustion chamber	Stationary	n/a	$0.5-2 million	[1]FAO 2008, [2]Duku et al 2011, [3]Kristofferson 1986

Reactor type	Process type	Capacity	Construction materials	Conversion efficiency (mass%)	Energy source	Residence time	Emissions	Fixed Carbon (mass%)	Auxiliary requirements	Portability/permanence	Working life	Capital Cost	Reference(s)
Rotary, Pro-Natura Pyro 7 rotary/ screw	Continuous			20-30	Ext heat & volatile combustion		Low	High quality	Electricity			High	FAO 2008, Duku et al 2011, Pro-Natura 2004
JMU horizontal drum, Meko kiln, UDSM experimental kiln	Batch[1], Semi-batch[3]	6-7 kg/batch[1], 113 L, 200 L[3]	Concrete block, fire brick, steel plate, drum & pipe	19-24[1]	Ext. heat & volatile combustion	60 min (hot period)[1], 13 hrs (wood)[2]			None			$800[1],	[1]Prins et al 2011, [2]KFS 2013, [3]Ephata, 2014
Continuous multiple hearth	Continuous	2.75 tph charcoal[1]	Steel vessel and piping components	25-30[2]	Volatile combustion	n/a	CO_2: 492 g/kg charcoal CO: 160 g /kg charcoal CH_4: 50 g /kg charcoal TSP: 200 g /kg charcoal[1]	n/a	Electricity (fan & motorized drive), gas recirculation piping	Stationary	n/a	n/a	[1]EPA 1995, [2]Duku et al 2011
FLASH													
HNEI Flash Carbonization	Batch	594 tpy/m3[3]	Steel vessel and piping components	30-40[1], 34-50[2,4]	Partial combustion	20 min[1]	n/a	43-81[1]	Compressed air source, electrical ignition	Stationary	n/a	€180/ton charcoal[3]	[1]Antal et al. 2003, [2]FAO 2008, BTG[3], [4]Duku et al 2011

n/a = not available
EGR = exhaust gas recovery
tph = tonne per hour
tpd = tonne per day
tpy = tonne per year
TSP = Total Suspended Particulates



Picture 4: Traditional earth mound charcoal kilns in Liberia (source: BBC, 2012)



Picture 5: Brazilian beehive kiln (photo: P. Girard)



Picture 6: JMU horizontal drum retort kiln (Prins et al., 2011)



Picture 7: UDSM horizontal drum retort (Ephata, 2014)



Picture 8: Mark V charcoal kiln (FAO, 1996)



Picture 9: Lighting a D-Lab kiln in El Salvador (photo: D. Sweeney)



Picture 10: Lambiotte kiln (FAO, 2008)



Picture 11: Pro Natura pyrolyzer (http://www.biochar-international.org/)



Picture 12: Adam retort (http://biochar.bioenergylists.org/content/freefarm-adam-retort)

4.4 Products of slow pyrolysis

As shown in Table 4, the pyrolysis process results in three types of products with varying fraction, depending on the mode of pyrolysis and its operational parameters: a carbonaceous solid (char), liquids (tars and oils) and permanent gases, which are described in more detail hereafter.

4.4.1 Product characteristics

- **Charcoal**

Charcoal yield is influenced by many factors. Pyrolysis conditions that favour high char yields are (Czernik, 2008; Duku et al., 2012):

- High lignin, ash and nitrogen content in biomass
- Low pyrolysis temperature (<400°C), but low teperature also results in lower fixed carbon content
- High process pressure (1 MPa), because a higher concentration of pyrolysis vapour increases the rate of secondary reactions
- Long vapour residence time because extended vapour/solid contact promotes secondary char forming reactions
- Low heating rate because it slows formation of organic vapours and increase residence time
- Large particle size as low thermal conductivity of biomass results in slow heat and mass transfer rate within particles
- Optimized heat integration, such as minimized biomass burn off

Table 9 presents the calculated yields based on stoichiometry, thermodynamic laws and practical experiences.

Table 9: Stoichiometric, thermodynamic and practical charcoal yields (Czernik, 2008)

	Equation	Char yield	
		% by weight	*% C*
Stoichiometric	$CH_{1.4}O_{0.6} \rightarrow CH_{0.2}+0.6H_2O$	53.0% by weight	100% C
Thermodynamic (Cellulose)	$C_6H_{10}O_5 \rightarrow 3.74C+2.65H_2O+1.17CO_2+1.08CH_4$	27.7% by weight	62.4% C
Practical	$CH_{1.4}O_{0.6} \rightarrow$ charcoal + gas + liquid	10-35% by weight	15-60% C

Charcoal intended for domestic cooking typically contains 20-30% volatile matter (with a value of 40% being marginally acceptable) (Antal and Grønli, 2003). The ash content of a good-quality charcoal typically lies between 0.5 and 5%, resulting in a range of calorific values between 28 and 33 MJ/kg (Foley, 1986). The ash content of the feedstock varies widely and influences the yield of char (Demirbas, 2004; Amonette et al., 2009). Generally, woody feedstock produces char which contains low proportions of ash (<1% by weight), whereas biomass with high mineral content, i.e., grass, grain husks and straw residues, produce char with high ash contents (Demirbas, 2004). These feedstocks may contain ash content up to 24%, or even 41% by weight, such as rice husk and rice hulls, respectively (Duku et al., 2012).Beyond its proximate analysis, the quality of a charcoal can be represented by many other properties. These include: moisture content, calorific value, elemental composition, hardness (abrasion resistance), compressive strength, bulk and true densities, surface area, porosity and pore volume distribution, electrical resistivity, and reactivity (Antal and Grønli, 2003).

In terms of combustion properties, the energy content of charcoal briquettes tends to be lower than that of wood charcoal (22–29 MJ/kg versus 31–33 MJ/kg, respectively). Briquettes, in general, have more volatile matter than wood charcoal; hence, to burn briquettes efficiently, combustion equipment (whether stoves or boilers) must be retrofitted or redesigned. Additionally, the brittleness and higher ash content of the briquettes implies that users accustomed to wood charcoal must undertake seemingly small – but important – changes in the handling of briquettes (Mwampamba et al., 2012).

Impact of Moisture Content in Charcoal

The heating value of an organic fuel is influenced more by its moisture content than by the type of biomass. Because moisture content is highly variable, comparisons between fuel types are always made on dry matter basis. There exists a linear correlation between moisture content and heating value of the total substrate (see Figure 12) (Hartmann, 2012).

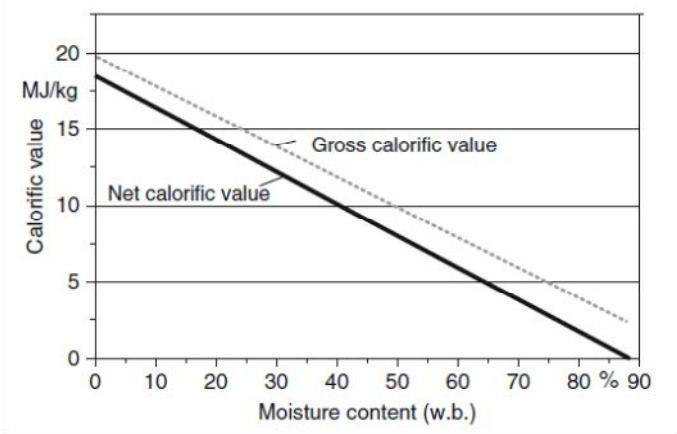


Figure 12: Relationship of gross (HHV) and net (LHV) calorific values of ash-free biomass with fuel moisture contents (Hartmann, 2012)

For the actual estimation of energy content, the as-received heating value of the organic fuel has to be calculated accounting for moisture content of the biomass (equation 5).

$$H_u = \frac{H_{u(wf)}\ (100-w)-2.443\ w}{100} \qquad (5)$$

Where H_u is the actual heating value of the biomass (in MJ/kg) at a certain moisture content w (in %), $H_{u(wf)}$ is the moisture-free heating value of the biomass. The constant 2.443 is the heat of evaporation of water in MJ/kg at 25°C (Kaltschmitt et al., 2009).

Impact of Ash Content in Charcoal

Ash influences the net calorific values of the organic biofuels.

Figure 13 demonstrates this dependency. The usually low ash content in wood-based fuels leads to a relatively low impact of ash in calorific value. However, if heavy secondary pollution with minerals and other contaminants occur during harvesting and handling, the ash content can increase (Hartmann, 2012).

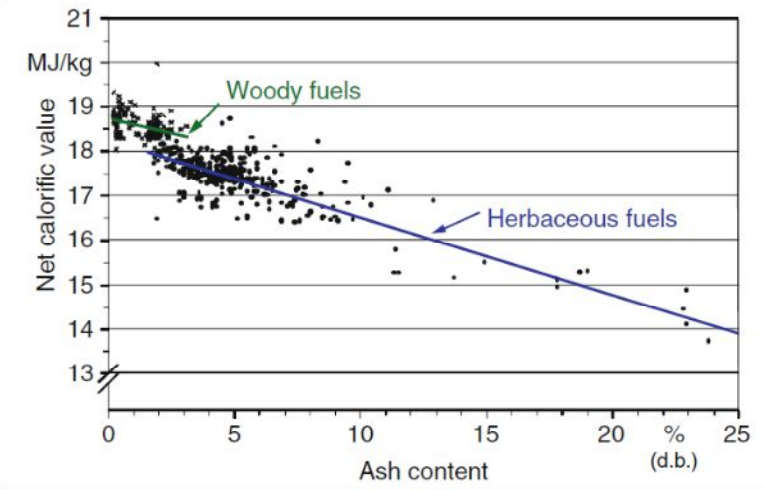


Figure 13: Negative correlation of net calorific value with ash content for several species of wood and herbaceous fuels (dry-basis) (Hartmann, 2012)

- **Liquid**

The major composition of bio-oils produced via pyrolysis are organic acids, esters, alcohols, ketones, phenols, aldehydes, alkenes, furfurals, sugars and some inorganic species (Mohan et al., 2006). They have significant heating values (13-18 MJ/kg), and they can be converted into valuable chemicals, fuels, and distillates used in engines and turbines for power generation. Bio-oils, complex mixtures of at least 74 different compounds, are recognized as being toxic, mainly because of the low pH and high concentrations of phenolic compounds, which can cause eye damage, but not skin damage, and have been demonstrated to be non-mutagenic (Overend, 2008).
With the utilization of bio-oils as transportation fuels, there are numerous associated technical bottlenecks due to their crude and inconsistent nature, thermal instability, and corrosive properties (Sriragan et al., 2012). As a result, several strenuous upgrading steps are required to ensure the applicability of these bio-oils as transportation fuels. Hydrodeoxygenation, catalytic cracking, emulsification, steam reforming, and chemical extraction are relevant techniques developed to improve the bio-oil quality (Zhang et al., 2007).

- **Gas**

The pyrolysis gases consist of condensable and non-condensable fractions. The condensable fraction contains methanol (CH_3OH), acetic acid (CH_3COOH), water vapour (H_2O), and tars (Brito, 1990; in Miranda et al., 2013). The non-condensable gases include gases, such as CO_2, CO, H_2, CH_4 and other light hydrocarbons, as well as particulate matter and more complex compounds like polycyclic aromatic hydrocarbons (PAHs). The exact combination of compounds present in the mixture depends on the original feedstock, as well as the temperature and rate of pyrolysis. The resulting mixture is flammable with a calorific value between 5 and 15 MJ/kg (Raveendran and Ganesh, 1996; in Miranda et al., 2013) or 11-22 MJ/Nm^3. During slow pyrolysis roughly 70% of the mass and 50% of the energy embodied in the woody feedstock escapes in the form of pyrolysis gases (Miranda et al., 2013).

4.4.2 Briquetting chain

Figure 14 presents the charcoal briquetting process chain. The production limiting step is the drying process which for open drying can take 2-5 days; hence, for continuous production there must be enough space to accommodate a minimum of 5 days output, and they need to be covered in the event of rain. Because of this, some micro-producers find it difficult to commit resources to their production (GVEP, 2010).



Figure 14: Process chain of charcoal-briquetting (GVEP, 2010)

Charcoal briquetting technology has existed in developing countries for at least 50 years. A key component in either system is the densification equipment (FAO, 1987). Five broad categories of briquetting equipment are available, in increasing order of cost they are hand press, agglomerator, screw extruder, roller press and ram/piston press. All technologies are suitable for briquetting carbonized feedstock (although the ram/piston press tends to be prohibitively costly). If the process is densify-first and then carbonize, however, screw extruder and ram/piston press are the only available options. In SSA, densification is almost exclusively carried out using hand presses, agglomerators and screw extruders because they are the only briquetting equipment that can be manufactured locally at a price competitive with imported equipment. The manufacture of pillow briquettors – which usually require cast iron rollers – can be achieved in only a few SSA countries; ram/piston presses are almost always imported from China or India. In addition to the factory installation, drying space seems to be a common challenge, regardless of the scale of operation. Lack of drying space and difficulties with drying in the rainy season are the main factors limiting the scale and consistency of production for most producers. For producers who are dependent on agricultural residues and seasonal raw materials (usually home-based industries), lower productivity or even temporary closure of operations occur during the rainy season (Mwampamba et al., 2012).

The higher the density, the higher is the energy/volume ratio. Hence, high-density products are desirable in terms of transportation, storage and handling. Charcoal briquettes should be easy to ignite, particularly for household and recreational cooking. Very low porosity, low volatile content and high ash content are likely to reduce the ignitability (Bhattacharya et al., 1990).

For an overview of briquetting technology see Grover and Mishra (1996).

4.4.3 Health- and environment-relevant emissions

Charcoal production can have negative health impacts during the production process and use. They are generally associated with smoke inhalation and carbon monoxide poisoning (Akpalu et al., 2011; Arnold et al., 2006; Ezzati and Kammen, 2001; IEA, 2010)

- **Emissions during pyrolysis process**

Carbonization takes place under limited supply of oxygen. Thus, apart from the emission of CO_2, NO_X and dust, products of incomplete combustion (PIC), such as CO, vapours and liquid C_XH_Y, soot and acids like formic and acetic acid, are released. Polycyclic aromatic hydrocarbons (PAHs) are also emitted, which are known to be carcinogenic (Vest, 2003).

Emissions from the charcoal-making process varies with a number of factors of which the most important are:

- Method of charcoal making (retort or kiln)
- Pyrolysis temperature
- Moisture content of input material
- Type of input biomass

Levy (1995) presents emissions from charcoal production in a retort (externally heated system) and in an autothermal kiln (Table 10 and Table 11).

Table 10: Main gas emissions during charcoal production in *retort* by Surrey University (Levy, 1995)

Gas		Temperature		
		500°C	600°C	800°C
Carbon dioxide (CO_2)	*Vol-%*	44.8	31.8	20.6
Carbon monoxide (CO)	*Vol-%*	33.5	30.5	34.1
Methane (CH_4)	*Vol-%*	12.4	15.9	13.7
Hydrogen (H_2)	*Vol-%*	5.56	16.6	28.6
Ethane (C_2H_6)	*Vol-%*	3.03	3.06	0.77
Ethylene (C_2H_4)	*Vol-%*	0.45	2.18	2.24

Table 11: Smoke test during charcoal production in an autothermal *kiln* by Cardiff University (Levy, 1995)

		30 min	1 hour	2 hours
Flue temperature	*°C*	200	85.9	86.1
Oxygen (O_2)	*%*	2	3.7	7.2
Carbon dioxide (CO_2)	*%*	18.6	17	13.5
Carbon monoxide (CO)	*%*	3.7	3.6	3.6
Nitrogen dioxide (NO_2)	*ppm*	400	200	140
Nitrogen oxide (NO_x)	*ppm*	1	0	0
Sulphur dioxide (SO_2)	*ppm*	215	68	29

Compared to earth mound kilns, retorts have reduced air pollution by up to approximately 75%, as the smoke produced is partly burned off during the carbonization process (Adam, 2009).

Kammen and Lew (1995) give an overview of emissions measured in different charcoal production systems (see Table 12). The production processes range from modern kilns in the US (Smith and Thorneloe, 1992; EPA AP-42, EPA Moscowitz, 1978; Briane and Doat, 1985) to mound kilns in developing countries (Lacaux et al., 1994; Hao et al., 1994). Apart from CO_2, CH_4, emissions are lower in mound kilns compared to modern kilns in the US. The levels of CO are comparable, and levels of NMHC and TSP cannot be compared because in the modern US kiln it included condensibles, tars and oils.

Table 12: Grams of emissions per kg of charcoal produced for several studies (Kammen and Lew, 1995)

		Dry mass yield	CO_2	CO	CH_4	NMHC	TSP
Source	Type of pyrolysis	%	g/kg	g/kg	g/kg	g/kg	g/kg
Smith and Thorneloe, 1992	US charcoal plant adjusted to reflect low efficiencies of earthen kilns	20	3300	443	147	405	320
Briane & Doat, 1985[1]	US kiln	31	1350	700	170	n/a	n/a
EPA AP-42	Modern kiln in US	n/a	n/a	172	52	157[2]	133[3]
Lacaux et al., 1994	Trad. mound kiln West Africa	28	1549	233	40	8	5
Hao et al., 1994	Mound kilns in Zambia	n/a	2629	86	18	n/a	n/a
EPA Moscowitz, 1978	Uncontrolled	25	n/a	160-179	44-57	7-60[4]	197-598
	Low controlled	25	n/a	24-27	6.6-8.6	1-9[5]	27-89
	Controlled continuous	25	n/a	8-8.9	2.2-2.9	0.4-3[6]	9.1-30

NMHC = Non-methane hydrocarbons (incl. recoverable methanol and acetic acid)
TSP = Total suspended particulates
[1] relatively modern kiln
[2] incl. condensibles and non condensibles
[3] incl. tars and oils
[4] 67-76 g/kg of methanol and 102-116 g/kg of acetic acid are included in this figure
[5] 10-11 g/kg of methanol and 15-17 g/kg of acetic acid are included in this figure
[6] 3.3-3.8 g/kg of methanol and 5.1-5.8 g/kg of acetic acid are included in this figure

In a continuous carbonization system, pyrolysis gases can be connected to a central flue and afterburner to mitigate atmospheric emissions of carbon monoxide (CO), volatile organic compounds (VOCs) and particulate matter (PM) (Yronwode, 2000). However, its control is difficult in batch-type kilns because the emissions only reach steady-state conditions for a short time, hence requiring more supervision if afterburners are employed (Brown, 2009).

- **Emissions during charcoal/char briquettes combustion**

In general, emissions from charcoal stoves are lower than those of firewood stoves (Bailis et al., 2005; Antal and Grønli, 2003; Smith et al., 2000). However, during cold start, charcoal stoves produce a large amount of smoke, which can annul the emission reduction (Maes and Verbist, 2012). Charcoal stoves are typically started outside and are only brought indoors after the charcoal is hot, when little smoke is produced and emissions of pollutants can be up to 90% lower than those of firewood (Bailis et al., 2005; Jetter and Kariher, 2009). However, charcoal stoves emit larger amounts of carbon monoxide (CO) than fuelwood stoves (Bailis et al., 2005; Smith et al., 2000; UNDP, 2000).

A study that measured the total emission factors of 17 polycyclic aromatic hydrocarbons (PAHs) and 10 genotoxic PAHs in Chinese households burning charcoal and honeycomb char briquettes revealed large differences in emissions. While emissions, based on weight basis, were 111.65 mg/kg when burning charcoal, only 18.41 mg/kg were measured using char briquettes. This indicates a twenty-fold decrease in emission using char briquettes compared to using charcoal for cooking and heating (Chen et al., 2004).

Although a thorough life-cycle analysis has yet to be conducted on the contribution of briquettes to air pollution and GHG emissions, briquettes could be expected to have slightly poorer emissions characteristics than charcoal (due to the presence of binders), but are perhaps better than those from firewood and

other biomass lower down the energy ladder. Convincing a household to shift from wood charcoal to briquettes for health reasons would be a false and probably ineffective marketing strategy. The absence of national standards to control the quality of briquettes (in terms of moisture content, fixed carbon, ash, volatiles and heating value) is often mentioned as a challenge hindering progress in the industry and slowing down market entry for briquettes (Mwampamba et al., 2012).

4.5 Safety issues

The fact that kilns and retorts are fairly simple to operate can cause operators to overlook basic safety practices. The operator needs to closely monitor weather conditions, the integrity of the kiln/retort structure, the temperature of the kiln, and the time of the process for every production cycle. Explosions, fire and carbon monoxide poisoning are the most significant hazards of char production. Workers should wear gloves when working around the kiln door and avoid tripping and falling. First aid material should be kept on site at all times (Garcia-Perez et al., 2011). The pyrolyzed product has to be cooled down before exposing it to oxygen, as otherwise spontaneous combustion can occur.

Figure 15 presents the flammability diagram with the concentration of nitrogen, oxygen and fuel (pyrolysis gases and vapours) on each side of the triangle. A mixture of oxygen, fuel and inert species (nitrogen) is flammable when the composition of the mixture falls in the flammable region of the triangular diagram. Two characteristics determine the flammability region of a lean fuel mixture such as the pyrolysis gases and vapours evolving from the pyrolysis reactor. The lower flammability limit (LFL) which describes the leanest mixture that can sustain a flame, and the limiting oxygen concentration (LOC) which describes the lowest oxygen concentration that can sustain a flame.

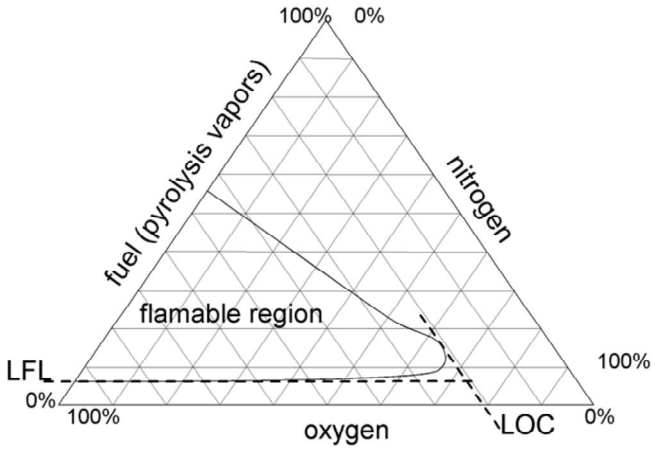


Figure 15: Flammability triangular diagram (Cuypers and Helsen, 2010)

Lynch and Joseph (2010) present guidelines for the development and testing of pyrolysis plants to ensure their safety to equipment operators and the general public, and to minimize contaminating emissions.

If the material needs to be dried before being fed into the pyrolysis system, the exhaust from drying systems must be monitored for volatile organic compounds (VOC), which arise from either vaporization of volatile components in the biomass or from thermal degradation of the biomass in the dryer. When volatile components are released, they give rise to a slightly smoky exhaust plume called 'blue haze', which can be hazardous (Cummer and Brown, 2002). These emissions are usually released when the temperature of the feedstock is greater than 100°C; therefore, an effort should be made to prevent the feedstock from reaching this temperature. Cleanup equipment, such as cyclones and adsorption beds, may be necessary to filter the exhaust plume prior to its release from the drying system (Brammer and Bridgewater, 1999). Risk of fire and/or explosion can also result from the ignition of a feedstock dust cloud in the dryer or from the ignition of combustible gases released from the feedstock during drying. If sufficient oxygen concentration is present (>10%) in the drying medium and a sufficiently high temperature is reached in the dryer, then ignition may occur (Brammer and Bridgewater, 1999).

5 Conclusion

Charcoal is a highly popular household cooking fuel, particularly in urban areas of low- and middle-income countries (LAMICs). Its demand is predicted to remain high for the next decade(s), partly due to rapid urban growth. Despite major efforts, the conceptualized shift from traditional fuels, such as firewood and dried animal dung, to cleaner fuels such as liquefied petroleum gas (LPG) and electricity, proceeds at a slower pace than anticipated due to persistently high poverty levels (affordability), infrastructural problems to access targeted alternatives (LPG, kerosene and electricity), and cultural factors. Studies suggest that for the majority of city residents there will be diversification of cooking fuels rather than fuel switching and charcoal will continue to be present in the fuel mix in the foreseeable future. Enhancing the sustainability of charcoal, including the use of alternative sources, thus needs to be envisaged.

Present production practices of wood-based charcoal, which are associated with unsustainable forest logging and low efficiency production methods, contribute to adverse effects on the environment, on biodiversity, local and global climates, agricultural productivity and watershed management.

Current solid waste management (SWM) in LAMICs, which is characterized by low waste collection rates and inappropriate disposal methods, also lead to environmental problems, such as water and soil pollution through leachate and uncontrolled emissions of greenhouse gases. In addition, SWM is often financially unsustainable. Local authorities and service providers generally look for ways to reduce the high financial burden of service provision. Increasing the value chain by sales of organic waste recycling products is seen as one possible option to improve the cost-recovery of a SWM system.

Development of appropriate solutions that enable low-tech conversion of municipal biowaste streams into a valuable renewable energy carrier would combine several benefits, including:

- Environmental benefits: reduction of greenhouse gas emissions resulting from inadequate solid waste management and unsustainable energy production
- Socio-political benefits: independence from unreliable supply and the fluctuating prices of fossil fuels
- Financial benefits: the use of renewable and locally available energy sources made from waste material will create business opportunities and generate employment.

To make this happen, certain things are essentially required, including the high availability and accessibility of suitable feedstock, economically viable waste-to-char-briquette-production and user acceptability. For low-cost carbonization of organic solid waste, the feedstock needs to be continuously available in substantial quantities at no or low cost. The required physical-chemical properties of the feedstock should be suitable for pyrolysis. This includes feedstock which is dry, unmixed, homogeneous, and uncontaminated. Feedstock should also be obtained near the source of generation to reduce collection and transport costs. The large bulk of the organic fraction of municipal solid waste, such as household and market wastes, are thus not feasible from a physical properties point-of-view as they are too wet and mixed and contaminated. For these types of wastes, biochemical conversion methods, such as anaerobic digestion, which require a wet environment, are more suitable.

It has been mentioned that promoting char briquettes mainly by pointing out the efficient use of waste products might limit the pool of potential customers who are not driven by environmental motives (Mwampamba et al., 2012). But, on the other hand, it is this logic that invites actors in the waste sector to get engaged, and it strives for reducing transportation costs and generating benefits from specific biowaste. A successfully operational waste-to-char supply chain would create business opportunities, and also provides the opportunity for individuals and groups to shoulder social responsibility.

It has to be acknowledged that this approach will not bring an end to all waste-related challenges in cities of low- and middle income countries. Furthermore, it will not solve all problems of the charcoal sector. However, it bears the potential of contributing to an improvement on the way towards a more sustainable future. Mainly due to the selectiveness of input materials, the impact of char-production from biowaste on a city-wide waste management scale is rather limited. Nevertheless, carbonization could be an interesting valorisation method for waste producers, collectors or service providers at material recovery

facilities, who have continuous access to suitable waste types and appropriate charring technology. At the same time, sustainably produced char briquettes could easily be absorbed by the huge charcoal market.

Traditional charcoal-making technologies are both energy-inefficient and highly polluting. Despite some exciting developments, further efforts are required to reach the following goals of advanced char production; these include (Brown, 2009):

- Recovery of co-products in a continuously-fed pyrolyzer to improve energy-efficiency, process economics, and reduction of pollution emissions associated with batch kilns.
- Exothermic operation without air infiltration to improve char yields and energy efficiency.
- Control of operating conditions to improve char properties and allow for changes in co-product yields.
- Feedstock flexibility, allowing both woody and herbaceous biomass to be converted to char.

As a consequence, areas for further research include:

- Combinations of technologies and biowaste types (next to markets or transfer stations):
    - Anaerobic Digestion for wet, mixed biowaste (biogas can be used to heat the pyrolyzers)
    - Slow pyrolysis for dry, unmixed biowaste
- Development of a continuously fed, low-cost pyrolysis system, offering high throughput and reduced energy input, and making use of all by-products (combustible pyrolysis gases and waste heat)
- Emission measurements during the production- and consumption-stage of char briquettes under varying operational conditions.
- Development of quality standards for pyrolysis and briquetting to ensure high-quality products
- Financial feasibility of small- and medium-scale pyrolysis systems (what kind of business model would be promising for a specific context?)
- Assess user acceptability of char briquette to improve marketing
- Explore other uses of char (e.g., soil amendment [Terra Preta movement] or activated carbon)
- Market studies for char utilization in industries (e.g., cement factories)

In industrialized countries, the commercial pyrolysis technologies seldom run alone with char output as end products. Most of them are combined with gasification and combustion of the pyrolysis gas products. However, these combined large-scale technologies are expensive and may not be appropriate and affordable in developing countries (Chen et al., 2014). A profitable business is often only realistic if charring and briquetting is done on a large-scale with continuous, energy-efficient operation. However, this requires high investment and entails high operational and maintenance costs, as well as different sets of operational and monitoring skills due to the increased complexity of the system.

Apart from the technological requirements mentioned above, other existing challenges remain. One of the key conclusions made by the World Bank (2009) when evaluating 'transformation of the current charcoal sector' is the necessity of addressing the broader regulatory and tax framework around which the sector operates. Unless the market cost of charcoal reflects its true value - which includes raw materials, labour, transport, and all taxes and licenses - any efforts to develop sustainably produced charcoal will always be undercut by illegal charcoal, which bypasses many of these key costs. Stronger enforcement of wood charcoal laws to decrease large price gaps (e.g., in Tanzania, where VAT is chargeable on briquettes and wood charcoal, but entirely avoided by producers of the latter) is often cited by producers as a necessary intervention (Mwampamba et al., 2012). Market prices of illegal and regulated charcoal can be balanced in two ways: either by subsidizing the costs of regulated charcoal, or by imposing a financial penalty on illegally produced charcoal. While the former poses the question of financial sustainability, the latter requires complementary enforcement efforts to increase costs on illegal producers, with the expected results of greater compliance in the future. Ultimately, a mix of both approaches may be necessary to increase market penetration of alternative charcoal. Achieving greater compliance of the informal and currently illegal sector will result in an increase in prices to consumers, but this will in turn stimulate efforts to increase efficiency in production and use of alternative substrates. Formalizing and regulating an important sector, such as the charcoal sector, requires strong levels of political support and willingness to challenge powerful and vested interests - often with strong links to the political establishment (World Bank, 2009).

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