Burning Nigerian forests on European barbecues

A carbon footprint and cost comparison between imported Nigerian charcoal and sustainably produced charcoal in the European Union

by

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Executive summary

In Western countries charcoal is considered as a luxury product for recreational barbecuing. On the other hand, in developing countries, charcoal is a traditional biomass source used for heating and cooking. In developing countries, charcoal production is accompanied with more greenhouse gas [GHG] emissions than in developed countries. This is often the result of an unregulated charcoal sector in developing countries, where charcoal production is associated with uncontrolled harvesting and the use of traditional, inefficient production methods. The majority of global charcoal production over the last 50 years took place in Africa. Within Africa, Nigeria is the largest charcoal producer and the country with the highest absolute emissions regarding charcoal production. In 2016, Nigeria exported around 4.4% of its total charcoal production, accounting for 196 ktonnes. More than 75% of this export was imported by the European Union [EU]. Nigeria was the EU's biggest charcoal supplier, accounting for around 21% of the total EU's charcoal import; therefore, the consumers in the EU has a responsibility regarding the environmental impact associated with this charcoal import. Between 2003 and 2016, the EU's charcoal import from extra-EU has more than doubled, imports from Nigeria have increased even more, by 5.5 times.

This research examines a shift of the EU's import from Nigerian charcoal to sustainably produced charcoal in the EU. There is a knowledge gap regarding the amount of GHG emissions caused by the EU's import of Nigerian charcoal. Additionally, the difference in production costs has not been quantified yet. This research answers the following two main research questions:

1. *How much greenhouse gas emissions caused by the European Union's import of Nigerian charcoal may be mitigated by shifting production sustainably to the European Union?*
2. *How economically feasible is it for the European Union to shift imports from Nigerian charcoal to sustainably produced charcoal in the European Union?*

The research questions are answered by performing three analyses. First, a trade database comparison [TDC] is conducted to map the EU's charcoal import. Then, a single-impact life cycle assessment [LCA], also called a carbon footprint, is used to determine the global warming potential [GWP] in gram CO_2 equivalent per MJ charcoal combusted in the end-use stage for a 100-year time interval. This LCA only considers a single environmental impact category and does not give an overview of the full environmental impacts. Finally, an economic analysis [EA] is

executed to determine the production costs and benefits, together with the net present value [NPV]. The three analyses are performed for two scenarios. In the first scenario, *Scenario NG*, the charcoal is produced in Nigeria and in the second scenario, *Scenario EU*, the charcoal is produced within the EU, specifically in Finland. In both scenarios, the charcoal is transported to and consumed in the Netherlands. The charcoal supply chain is considered within these analyses and consists of the following five stages: biomass production, feedstock logistics, conversion, distribution logistics and the end-use. Figure A illustrates the main results of the LCA and EA.

As shown in Figure A, the GWP for *Scenario NG* is 284 g CO_2 -eq/MJ. In *Scenario NG*, 55% of the greenhouse gas [GHG] emissions are released during wood carbonisation in the conversion stage and 41% is released during charcoal combustion in the end-use stage. In 2016, nearly 147 ktonnes of charcoal was imported by the EU from Nigeria, which cause a total of approximately 1.25 Mtonnes CO_2-eq to be released.[1]

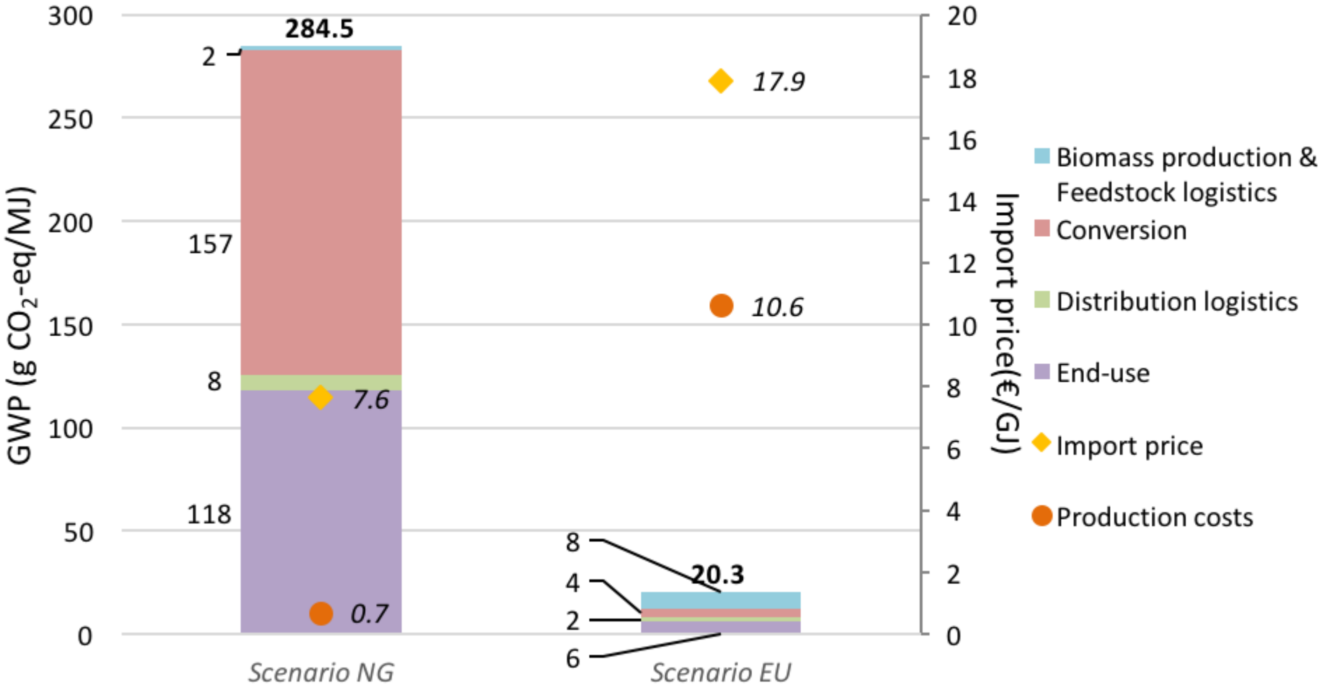

Figure A. The GWP, production costs and import price for *Scenario NG* and *Scenario EU*.

The GWP for *Scenario EU* is 20.3 g CO_2 -eq/MJ and the largest contributor is biomass production and feedstock logistics stage which accounts for 40% of the GHG emissions. The end-use stage is also a major contributor accounting for 29% of the total GWP. The cause for this high GWP of

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[1] Assuming a lower heating value of 30 MJ/kg for charcoal.

this stage is due to methane being released by incomplete combustion of charcoal, a potent GHG, making a significant contribution to the GWP balance of *Scenario EU*.

The total GWP for *Scenario NG* is over 10 times larger than the GWP for *Scenario EU*. This large difference is caused by two reasons. Firstly, due to the use of traditional kilns in *Scenario NG* in contrast to *Scenario EU* where more efficient industrial kilns are employed. Secondly, due to unsustainable forestry in *Scenario NG*, while in *Scenario EU* sustainable forestry is considered. In the case of unsustainable forestry, harvested trees are not replanted. The biogenic CO_2 emissions released in the conversion and end-use stage are not sequestrated; therefore, these biogenic CO_2 emissions are accounted for and included in the total GWP of *Scenario NG*. In *Scenario EU* trees are replanted after harvesting and thus the biogenic CO_2 emissions released are not included in the total GWP of *Scenario EU*, since these are considered carbon neutral.

Based on the import quantity of 2016, a total of 1.16 Mtonnes of CO_2-eq could be mitigated per year by replacing the currently amount of imported unsustainable Nigerian charcoal with sustainable produced charcoal from the EU. Given the fact that a large fraction of other charcoal is imported from other developing countries, with similar conditions, the total emissions caused by the EU imports are likely even much higher.

Figure A also illustrates the large difference in import price the EU pays for Nigerian charcoal compared to the import price the EU pays for intra-EU charcoal. In 2016, the EU's import price for Nigerian charcoal was 7.63 €/GJ charcoal, while for intra-EU charcoal the import price was more than twice as high, namely 17.9 €/GJ.

From the cost-benefit analysis it became clear that charcoal production in Nigeria is only economically viable, resulting in a positive NPV, when the feedstock is obtained for free, low initial investments and another crucial condition is that the Nigerian labour costs are the bare minimum. Nigerian charcoal is sold below its true market value creating a vicious circle of unregulated harvesting and the use of inefficient production methods. From Figure A it is also clear that the vast majority of profits is made by middlemen.

This research found that under current conditions, without external support, it is not feasible to shift the EU's import of unsustainable charcoal from Nigeria to sustainably produced charcoal in the EU. The EU's import price for Nigerian charcoal is 7.63 €/GJ and lies below the production costs of sustainably produced charcoal in the EU, namely 10.6 €/GJ.

Several policy proposals have been attempted to improve the Nigerian charcoal sector or to reduce the import to the EU. Both the EU and Nigeria have tried to ban charcoal trade; however, this did not succeed. This research, therefore, recommends a carbon-tax of at least 50 €/tonne CO_2. The EU's import price for Nigerian charcoal then increases to 21.8 €/GJ, while indigenous charcoal will then cost 18.3 €/GJ.[2] This allows charcoal produced in the EU to compete with Nigerian charcoal. The question remains whether a carbon-tax on charcoal alone would be feasible and productive and if it will work better in practice than a charcoal ban, however, this goes beyond the purpose of this thesis and could be investigated in further research.

One thing is clear, measures have to be taken to halt the EU's import of unsustainable charcoal from places where there is no proof of sustainable forestry. By importing cheap charcoal from Nigeria, more GHG emissions than necessary are emitted. Secondly, it puts extra pressure on Nigerian forests, while deforestation rates are already high. Finally, it contributes to the maintenance of the current charcoal sector in Nigeria where charcoal producers only earn the bare minimum.

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[2] The carbon-tax is applied for both charcoal from Nigeria as from the EU.

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1. Introduction

Charcoal is considered as a luxury product for recreational barbecuing in Western countries (Reumerman & Frederiks, 2002). On the other hand, in developing countries, charcoal is a traditional biomass source used for heating and cooking (Anozie et al., 2007; Sedano et al., 2016). The production of charcoal in developing countries, however, has severe ecological and environmental effects (Chidumayo & Gumbo, 2013), as well as a considerable impact on human health caused by local air pollution (Zulu & Richardson, 2013). This is often the result of an unregulated charcoal sector, associated with uncontrolled harvesting and traditional production methods (Anozie et al., 2007; Jamala et al., 2013; Stassen, 2015).

The concerns regarding uncontrolled harvesting and traditional production are acknowledged by governments, policy makers and various non-governmental organisations (Chidumayo & Gumbo, 2013). Firstly, it is frequently pointed out that unsustainable wood harvesting for charcoal production leads to forest degradation and in some cases even to deforestation (Chidumayo & Gumbo, 2013; Sedano et al., 2016). The clearance or change in forest cover caused by human activities contributes to 6% - 17% of the global anthropogenic carbon dioxide [CO_2] emissions (Baccini et al., 2012; Bailis et al., 2015; Sedano et al., 2016). Secondly, in developing countries the majority of charcoal is produced with inefficient traditional production methods, causing in addition to CO_2, methane [CH_4], which is another greenhouse gas [GHG], and other pollutants to be emitted due to incomplete combustion (Bailis et al., 2015; Chidumayo & Gumbo, 2013; Kituyi, 2004). Additionally, according to Stassen (2015), in the worst case it can take up to ten tonnes of oven-dry wood to produce one tonne of charcoal. In contrast, contemporary industrial technologies with advanced drying procedures and efficient heat management (Antal & Grønli, 2003) only need around three to four tonnes of oven-dry wood to produce one tonne of charcoal (Van Dam, 2017), thereby limiting emissions and the related environmental impacts.

1.1 Charcoal in the global context

Africa is the largest producer in the world and it has been for over 50 years (Hillring, 2006). The continent accounts for 61% of global wood charcoal production over the period 2011 - 2015 (FAOstat, 2017). In 2015, the annual charcoal consumption per capita in Africa was 28 kg, while in Europe it was only 2 kg per capita (FAO Statistics, 2017).[3] Especially Sub-Saharan Africa [SSA] has a high charcoal consumption due to charcoal being the main energy source where most consumption takes place in urban areas (Van Dam, 2017; Jamala et al., 2013). This region has been the focus of several reports. Among others, the World Agroforestry Centre, the NL Agency and the World Future Council investigated the aforementioned concerns and suggested improvements to make the SSA charcoal sector more sustainable. The World Agroforestry Centre published a report about the key areas where interventions are needed (Neufeldt et al., 2015), NL Agency focussed on assessing bottlenecks with possible solutions (Vos & Vis, 2010), while the World Future Council's focus was on policy solutions (Neuberger, 2015). Within SSA, Nigeria is the biggest charcoal producer and consumer, and ranks second to Brazil globally (FAO Statistics, 2017). According to Bailis et al. (2015), Nigeria also has the highest absolute emissions from charcoal production in Africa.[4]

Since 2011, Nigeria produces more than four Mtonnes of charcoal per year (FAO Statistics, 2017). In 2016, Nigeria exported nearly 5% of this initial production, around 196 ktonnes of charcoal (ITC, 2017). More than 75% of this export was imported by the European Union [EU]. In the same year, Nigeria was also the EU's biggest charcoal supplier accounting for 658 ktonnes or 21.4% of total EU's charcoal import from outside the EU (EC, 2017). FAO Statistics (2017) estimated that in total the EU consumed 972 ktonnes of charcoal in 2015. The extent of the impact of the EU's import of Nigerian charcoal however, has not been quantified yet to the knowledge of the author. Therefore, this thesis focuses specifically on the EU's charcoal import from Nigeria. Between 2003 and 2016, the EU's charcoal import quantity from countries outside the EU has more than doubled, while imports from Nigeria to the EU over the same period have increased by 5.5 times (EC, 2017). However, the reason for this large increase in import from Nigeria is not found in scientific literature. It is very likely that this is caused by an economic reason, therefore this thesis explores the economic aspect and does not consider other drivers, such as the product quality. The next section discusses relevant literature.

1.2 Previous research

The local environmental impacts and related GHG emissions regarding charcoal production and consumption have been widely discussed in the academic world. There are some older papers; however, still relevant nowadays. For example, in 1990, Antal et al. published a review of methods

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[3] In Europe; Albania, Bosnia and Herzegovina, and Norway are the largest consumers per capita (FAO Statistics, 2017).

[4] This information can be found in the supplementary information of Bailis et al. (2015).

for improving the yield of charcoal from biomass, discussing among others the effect of feedstock type, thermal pre-treatment and heating rate. Since traditional production methods are still used today and the technique has not changed much, this review is still relevant.

A considerable amount of literature has been published on charcoal in tropical ecosystems, discussing all kinds of environmental impacts. Chidumayo and Gumbo (2013) assessed the impact of charcoal production on soil and ecosystem services. Ezzati and Kammen (2002) focussed on the impact of charcoal combustion on human health. Much has been written about emissions to air and the related environmental problems specifically in Africa as it is the world's largest charcoal producer and consumer (Kammen & Lew, 2005; Kituyi, 2004). Lacaux et al. published a paper, as early as 1994, in which they indicated atmospheric pollution in the African Tropics due to traditional charcoal making. Recently, an important study *The charcoal transition: Greening the charcoal value chain to mitigate climate change and improve local livelihoods* from Van Dam (2017) commissioned by the Food and Agricultural Organisation of the United Nations [FAO] was published. This report gives a comprehensive overview of the GHG emissions associated with various production methods and the use of different cooking stoves. The key lesson from this research is that reducing GHG emissions can be achieved in all stages of the charcoal supply chain, particularly in the wood sourcing and carbonisation stage (Van Dam, 2017).

Another focus of literature has been on the effects of charcoal production in specific countries within SSA: the social and environmental impacts in Liberia (Jones, 2015), emissions of GHGs in Kenya (Pennise et al., 2001), and the economics of charcoal production in Tanzania (Luoga et al., 2000). Nigerian charcoal has also been the focus of some scholars. Tunde et al. (2013) looked at the health of the producers as well as the environmental impact in Nigeria, but does not quantify these impacts. Jelili et al. (2015) researched the socio-economic impact of charcoal production. Finally, Aiyeloja and Chima (2011) discussed the economic consequences of charcoal production in Oyo State, Nigeria.

Finally, as recently identified by San Miguel et al. (2017): 'Another key issue not sufficiently covered in the scientific literature relates to the application of modern carbonisation and pollution abatement technologies, which may improve environmental performance due to increased carbon yields and reduced air emissions.' (p. 1).

1.3 Research gap & research questions

In short, Nigerian charcoal is produced with inefficient production methods associated with environmental impacts. As shown above, the impacts of the charcoal sector from a local perspective have largely been covered by previous research. However, the environmental effect of the Nigerian charcoal trade has not yet been addressed. No scientific studies were found that discuss the impact of intercontinental charcoal trade, specifically the amount of emissions caused by the EU's import of Nigerian charcoal. Also, a proper economic analysis of the difference in cost structure between Nigerian charcoal production and sustainably produced charcoal in the EU is lacking. This research takes the EU's perspective on charcoal import from Nigeria and explores environmental and economic aspects of shifting the EU's charcoal imports from Nigeria to sustainably produced charcoal in the EU. Therefore, this research answers the two main research questions and its sub-questions:

1. *How much greenhouse gas emissions caused by the European Union's import of Nigerian charcoal may be mitigated by shifting production sustainably to the European Union?*
    a. *What is the annual European Union's charcoal import from Nigeria in quantity and monetary value?*
    b. *How much greenhouse gas emissions are annually caused by the European Union's import of Nigerian charcoal?*
    c. *What is the difference in greenhouse gas emissions between charcoal from Nigeria and sustainably produced charcoal in the European Union?*
2. *How economically feasible is it for the European Union to shift imports from Nigerian charcoal to sustainably produced charcoal in the European Union?*
    a. *What is the difference between the European Union's import prices for charcoal from Nigeria and the European Union?*
    b. *What is the difference in the associated production costs and benefits between Nigerian charcoal and sustainable charcoal from the European Union?*

A preliminary literature scan showed that imported unsustainable charcoal has a lower price than indigenously sustainably produced charcoal from the EU, even including transportation costs (Bawden, 2015). In the case that it is confirmed in this research that the imported Nigerian charcoal is unsustainable and has a lower import price than charcoal from the EU, the last sub-question is explored:

    c. *What kind of policy measures could be implemented to prevent unsustainable charcoal import from Nigeria?*

1.4 Scope

To answer the research questions, this research conducts three analysis: a trade database comparison [TDC], a life cycle assessment [LCA] and an economic analysis [EA]. The TDC will map the current charcoal trade. An attributional LCA will determine the difference in global warming potential [GWP] and the EA will estimate the costs and benefits of charcoal production. This research considers two case studies, called scenarios. In the first scenario, the charcoal is produced in Nigeria and in the second scenario the charcoal is produced sustainably within the EU, specifically Finland, while in both scenarios the charcoal is transported to and consumed in the Netherlands. This research takes a contemporary timeframe for both scenarios.

The concerns around climate change ask for an increased share of clean energy and GHG emissions reduction (Ben-Iwo et al., 2016). Climate change is also an essential environmental impact category within energy use (Blok & Nieuwlaar, 2016). Therefore, due to constrained time and resources, the LCA conducted in this research focuses on one single environmental impact: GWP. LCA is a widely-used tool for bioenergy systems to analyse and quantify the environmental impact and energy balance of various products. Besides the GWP, there are all sorts of other aspects that have a potential environmental impact, such as deforestation, which has an impact on biodiversity, volatile emissions that are harmful to both humans and animals, and the local impact of charcoal production on multiple socio-economic aspects. While these aspects are very important, this research only considers the GWP.

1.5 Wider relevance

The EU is in the process of creating a more sustainable energy sector to reduce GHG emissions in order to fight climate change (European Commission, 2015). This research contributes to a better understanding on the impact of the EU's import of Nigerian charcoal. The EU is aware of the negative ecological consequences associated with charcoal production in Nigeria (European Commission, 2013), while imports of Nigerian charcoal has increased over the last decade. This research addresses this discrepancy and aims to provides measures to influence this market behaviour.

CO_2 emissions are released both in Nigeria during charcoal production and in the EU during the combustion of charcoal. These emissions are generally not considered in the EU, because charcoal is a biomass and thus considered as CO_2 neutral[5] (Olsthoorn, 2006). However, when

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[5] Since biomass sequestrates CO_2 during growth, the CO_2 emitted during biomass combustion is not considered to contribute to net CO_2 emissions.

biomass is not replanted, these emissions do contribute to the net CO_2 emissions. These “forgotten” emissions are examined and by doing so, this research creates awareness on the importance of the charcoal’s origin.

While this research focusses on the trade between Nigeria and the EU, this research addresses a global problem of unsustainable forestry to produce cheap charcoal for exports. Indonesia is the largest exporter worldwide and exports almost 14.3% of the total global export, while Brazil is the largest charcoal producer globally (FAO Statistics, 2017). Both these countries suffer high annual deforestation rates, partly caused by charcoal production (Van Wesenbeeck, 2016).

In short, this research aims to create awareness on the importance of the charcoal’s origin. Moreover, the research’s results can contribute to create or alter policies in the EU, specifically focussing on mitigating climate change associated with charcoal imports.

1.6 Research outline

After this introductory chapter, the paper is structured as follows. The second chapter lays out the theoretical background of the LCA and EA, and explains the general charcoal supply chain. Then, an in-depth overview of the charcoal supply chains for the two scenarios is given in the case study. The fourth chapter is concerned with the methodology used for this study, explaining how the two main research questions are answered by conducting the three analyses. The results chapter presents the findings of the research. Also, for the LCA and EA, a combined sensitivity and uncertainty analysis is included. The limitations of this research and areas for further research are presented in the discussion chapter. Finally, the research questions are answered in the conclusion.

2. Theoretical background

This chapter gives a theoretical background of the life cycle assessment [LCA] and economic analysis [EA] used within this research. This is followed by a general description of the charcoal supply chain.

2.1 Life cycle assessment

An LCA is a tool to analyse the environmental impact of a product or service[6] (Baumann & Tillman, 2004). If a full LCA is performed, it will include all the activities associated with the product. This is often referred to as the life cycle of the product, from the moment that the raw material is extracted until it is recycled or discarded. In other words, this is called the life cycle model from cradle to grave, as illustrated in Figure 1. The boxes in this figure illustrate physical operations and the arrows demonstrate matter and energy flows. The life cycle is analysed and all input and output flows, which influence the overall impact, are quantified. Generally, these inputs are energy, water and raw materials, and the outputs are the identified pollutant emissions (emissions to air, emissions to water) and material waste (Baumann & Tillman, 2004). The outcomes will be interpreted to identify stages contributing the most to the environmental impact of a product or to compare the environmental impact of various products (Baumann & Tillman, 2004).

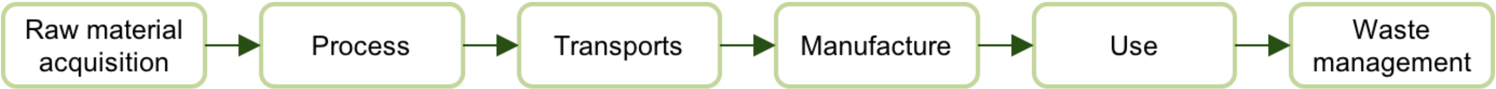

Figure 1. The life cycle model adapted from Baumann and Tillman (2004).

Since 1990, the International Standards Organisation [ISO] has standardised the LCA methodology through a series of standards (14040; 14044). These standards are now widely used. Based on the ISO standards, the European Commission constructed the International Reference Life Cycle Data System [ILCD] Handbook to ensure quality and consistency in LCA (Wolf et al., 2010). According to ISO the LCA consists of four stages: *goal and scope definition, inventory analysis, impact assessment and interpretation* (Baumann & Tillman, 2004). An LCA is an iterative process. Figure 2 illustrates the structure of a standard LCA study, including the procedural steps which are discussed hereafter.[7]

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[6] From this point forward, also for service there is referred to as product.

[7] *The Hitch Hiker's Guide to LCA: An orientation in life cycle assessment methodology and application* from Baumann and Tillman (2004) is recommended for more information about an LCA.

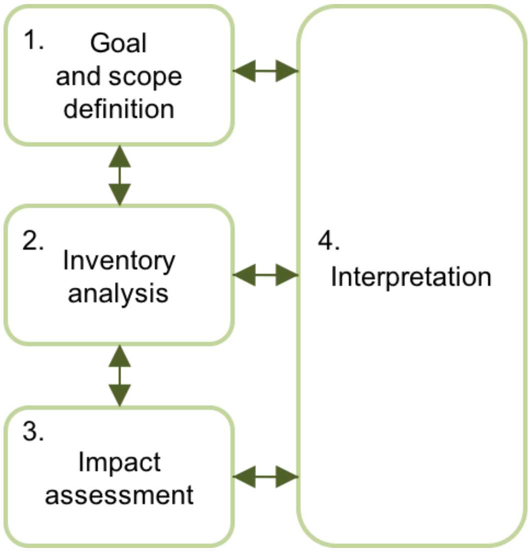

Figure 2. Standard LCA procedure adapted from Baumann and Tillman (2004).

2.1.1 Goal and scope definition

In order to carry out an LCA in a structured manner, the goal of the study needs to be identified. The motivation for the study as well as the target audience should be made clear (Baumann & Tillman, 2004). An LCA can be valuable to recognize life cycle stages with the largest environmental impact or to compare the environmental impact of competing products (Baumann & Tillman, 2004). It may be useful to develop policies, for example to mitigate climate change (Reijnders et al., 2012).

To define the scope of an LCA, it is important to specify the functional unit, system boundaries, impact type and the level of detail. The decisions made when defining the scope influence the correctness of the results.

The functional unit relates to the function of the product and not to the production or consumption volumes. Therefore, it must be measurable and all input and output flows should be quantified according to the same reference unit. This is especially important in a comparative study. This functional unit is defined in such a way so that it allows fair comparison between different end-products, since these products are rarely totally identical or can be of differing quality (Baumann & Tillman, 2004). The functional unit should be in line with the defined goal of the LCA.

Then, the system boundaries are defined in order to include the relevant processes and exclude irrelevant processes (Baumann & Tillman, 2004). It indicates which stages of the product life cycle from Figure 1 are taken into account. Examples are from cradle to grave, cradle to gate and gate to gate (Wolf et al., 2010).

Afterwards, the impact type is defined. The three general impact types that could be considered are: resource use, human health and ecological consequences (Baumann & Tillman, 2004). The data parameters that need to be collected in the *inventory analysis* are dependent on the choice of impact category made in the goal and scope definition (Baumann & Tillman, 2004). There are many different methods to execute an LCA and present its results. One of these differences is where in the cause-effect chain the impact is calculated, the point where the impact is calculated is called midpoint or endpoint. According to the *ILCD Handbook* from Wolf et al. (2010), the associated midpoint impact categories are "[...] climate change, (stratospheric) ozone depletion, human toxicity, respiratory inorganics, ionizing radiation, (ground-level) photochemical ozone formation, acidification (land and water), eutrophication (land and water), eco-toxicity, land use, and resource depletion (minerals, fossil and renewable energy resources, water)" (p. 109), as shown in Figure 3. The endpoint is the resulting impact of a midpoint category modelled all the way to the area of protection, which are either resource use, human health or ecological consequences (Figure 3). Finally, a complete LCA takes the full range of impact categories into account; however, throughout the years, single impact LCAs have been established, such as carbon footprinting and water footprinting, focussing on only one midpoint impact category.

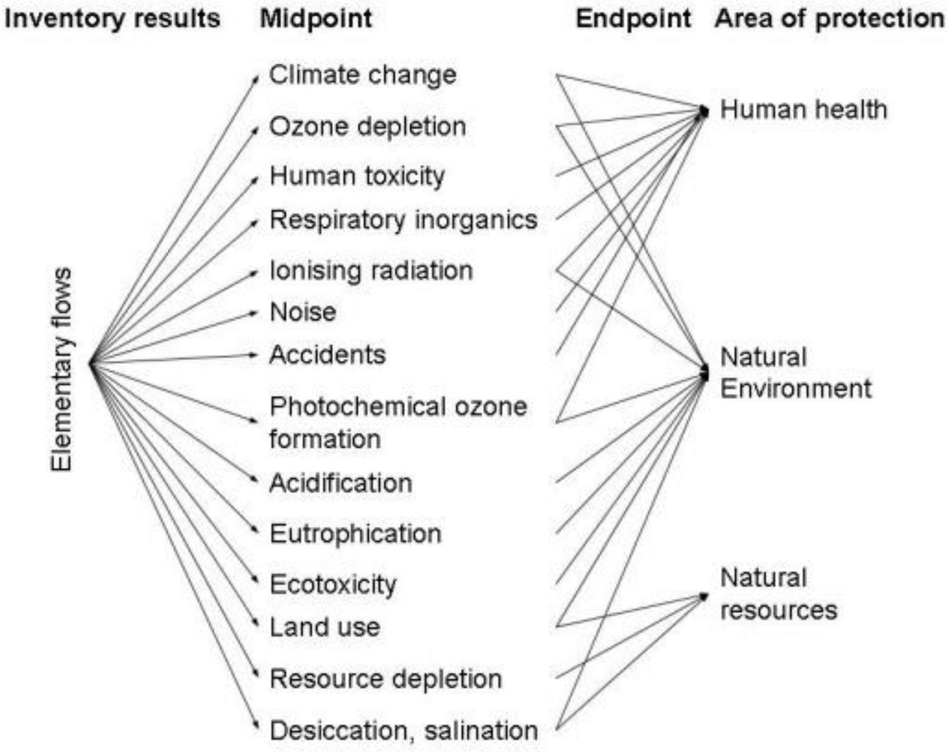

Figure 3. Impact categories midpoint vs. endpoint adapted from Wolf et al. (2010).

Finally, within the scope, the level of detail is clarified and thus the necessity for the type of data (Baumann & Tillman, 2004). For example, the collected data could be site or country specific.

2.1.2 Inventory analysis

After narrowing down the study within the first step, the inventory analysis is the second step. This step consists of quantifying the input and output flows of the product. There are two main life cycle inventory modelling principles: attributional and consequential (Wolf et al., 2010). 'Attributional' describes the actual supply chain and includes the end-of-life, while 'Consequential' depicts the theoretically expected supply chain as a result of some analysed change in the supply chain.

First a flow model is built for the specific system according to the system boundaries. An energy and/or mass balance is constructed that only considers relevant flows. Flows are considered relevant when they include scarce resources, harmful emissions for the environment/human health or other hazardous substances, depending on the type of impact chosen in *goal and scope definition* (Baumann & Tillman, 2004).

The next step is to collect all data for the various activities within the flow model, consisting of all inputs and outputs such as raw materials used, energy carriers, production processes, waste flows and emissions to air and water (Baumann & Tillman, 2004).

Finally, the collected data should be aligned with the functional unit. If there are different products produced in a process, this should be taken into account and partitioned. This is called allocation (Baumann & Tillman, 2004).

2.1.3 Impact assessment

In the life cycle impact assessment, the calculated impacts from the inventory analysis are adjusted to be more environmentally relevant. The aim is to interpret and evaluate the importance and meaning of the environmental impact. The two mandatory steps for the impact assessment are classification and characterisation (Baumann & Tillman, 2004). Normalisation and weighting are optional steps under ISO 14044 and could be included when multiple impact categories are considered.[8]

(1) Classification: The inventory parameters are sorted by impact type and the type of environmental impact category to which they contribute.

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[8] For more information about normalisation and weighting the *ILCD Handbook* from Wolf et al. (2010) could be consulted.

(2) Characterisation: The impacts of emissions or resource consumption per type of environmental load are calculated. Equivalency factors, also called equivalents, are used to sum up the total impact.

2.1.4 Interpretation

In order to interpret the raw results, the data should be clearly displayed (Baumann & Tillman, 2004). This can mean that only a selection of the data will be presented. Graphs, diagrams and tables help to give a clear overview. A part of the interpretation phase is to draw conclusions, containing a sensitivity analysis, uncertainty analysis and data quality assessment. In this final step, it is important that there is a reference to the original goal and scope definition (Wolf et al., 2010).

2.2 Economic analysis

This section covers an economic analysis in literature and how it can be applied, specifically, to an energy technology. First, the preparation for such an analysis is explained. Afterwards, the characterisation step is elaborated. Finally, the cost-benefit analysis is discussed, in which the net present value [NPV] is calculated. Unless otherwise indicated, the coming sections on the EA are based on *Introduction to Energy Analysis* from Blok and Nieuwlaar (2016).

2.2.1 Preparation

Several preparation steps should be taken into account in order to analyse the economics of an energy technology. The following preparatory steps are defined: aim; functionality; reference process; identify technology and system boundaries.

First the aim of the analysis should be determined. This step has similarities with the “Goal and scope definition” of the LCA. This includes why and for whom the study is carried out and determining the goal of the analysis. Within the aim of the study the time frame has to be considered. Finally, the level of accuracy and detail should be included.

Second, the functionality of the technology needs to be taken into consideration. The functionality should be defined in quantitative terms as much as possible, as this determines which technologies exactly are to be compared in the analysis.

Next, it is important that the reference technology is defined. This technology will serve as the basis to be compared against various alternatives. It is common practice to choose the most-used technology as reference. Another possibility is to consider the state-of-the-art technology.

When the previous steps have been taken, contemporary processes are analysed in the technology identification step. This is especially important when studying long-term alternatives for energy conversion and end-use. There are several methods to identify these technologies, such as scanning scientific and professional journals and interviewing experts.

Finally, it is necessary to define appropriate system boundaries in accordance with the aim of the analysis. Boundaries can be set as a single process, but can also cover a complete supply chain.

2.2.2 Technology characterisation

When preparation has been completed, the characteristics of the respective technology need to be determined. There are two important characteristics, namely: (1) technical performance and (2) costs. Technical performance is commonly expressed in either conversion efficiency or specific energy consumption, while the costs are expressed in cost per unit of energy output. Two type of costs can be distinguished: initial costs of investment and returning operation and maintenance costs.

2.2.3 Cost-benefit analysis

After characterising a specific technology, a cost-benefit analysis can be executed to provide insights on associated costs and benefits. A cost-benefit analysis is a process to evaluate business opportunities in terms of monetary value. Specifically, it attempts to compare the monetary value of a project's costs to its benefits (Cellini & Kee, 2015). The analysis is used to choose between alternative business opportunities. Typically, the costs of a project are subtracted from the benefits to obtain the net benefits or net costs. Since costs and benefits can occur at different times, all net benefits and net costs are ultimately discounted to their present value (Cellini & Kee, 2015). In the end, the NPV of a project can be calculated by subtracting the present value of net costs from the present value of net benefits. The NPV is an attempt to put a monetary value on a project, enabling comparison between multiple projects even though they have for example different time-frames or up-front investments. In financial terms, a project with a higher NPV is more favourable than one with a lower NPV. Projects with a negative NPV are considered as not financially viable.

While a cost-benefit analysis provides insight into the various costs and benefits associated with a project, it remains difficult to predict events that may influence the outcome of the analysis (Investopedia, 2018). Moreover, the outcome of a cost-benefit analysis is highly sensitive to its assumptions, especially the definition of the discount rate. Still, the analysis is particularly useful to map the various costs and benefits associated with a project and provide insights into which elements of a project contribute mostly to the NPV (Investopedia, 2018).

2.3 Charcoal supply chain

An environmentally and economically sustainable product requires an optimised supply chain (Hoefnagels et al., 2014). As indicated by several studies, changes in the supply chain can have environmental and economic consequences (Ekeh et al., 2014; Hoefnagels et al., 2014). For example, Hoefnagels et al. (2014) found that changing the logistics supply system can alter the competition between domestic use and exports. Searcy et al. (2014) established that improvements in moisture management, density and the quality of raw materials can reduce supply chain costs. By comparing supply chains of various products, the product with the lowest environmental impact can be identified (Daystar et al., 2013).

The charcoal supply chain represents the activities to produce and distribute charcoal from the raw material up to its customer. The charcoal supply consists of five main stages: biomass production, feedstock logistics, conversion, distribution logistics and the end-use (Anderson et al., 2016). The charcoal supply chain is illustrated in Figure 4 together with its relating activities.

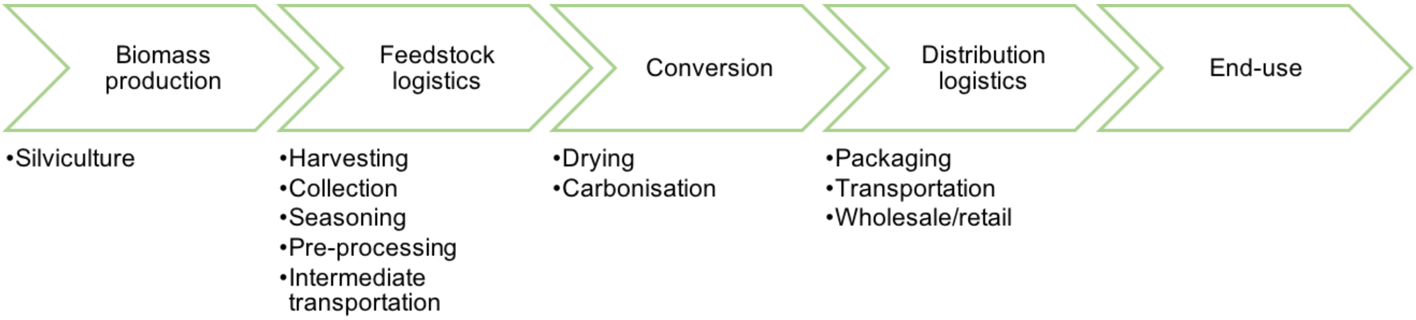

Figure 4. Charcoal supply chain with relating activities adapted from Anderson et al. (2016).

2.3.1 Biomass production

Charcoal can be produced from two types of raw material. The first is woody biomass to produce charcoal lumps (FAO, 1985). The second type of raw material consists of agricultural residues producing charcoal in a powder form. The powder needs an additional processing step, briquetting, in order to be able to use it (FAO, 1985). This thesis only focuses on charcoal lumps produced from trees. The charcoal sector distinguishes softwood and hardwood from trees (FAO, 2008). Hardwood typically produces a stronger and slower burning charcoal with a higher calorific value than softwood (FAO, 1985; Stassen, 2015). Therefore, hardwood is preferred for charcoal production all over the world (Adeniji et al, 2015).

The woody biomass either comes from natural forests or from man-made plantations (FAO, 1985). It is important to take the difference between sustainable and unsustainable forestry into account. As Work Green (n.d.) puts it, this difference "[…] comes down to whether the activities within the sector are depleting natural resources at a greater rate than the resource is being renewed." When considering hardwood from unmanaged natural forests, forest establishment is not included in the biomass production step, since the trees are generally not replanted (Daystar et al., 2013). However, for woody biomass from a purposely established plantation, management and maintenance of the plantation should be taken into account (Daystar et al., 2013). The growing, cultivation and maintenance of trees is called silviculture.

2.3.2 Feedstock logistics

The main activities in feedstock logistics are harvesting, collection, seasoning, (pre-)processing and intermediate transport to the kiln (Anderson et al., 2016; FAO, 1985a). These activities are discussed in the next sections.

First, trees are felled during harvesting. The three main types of harvesting woody biomass for charcoal production are: Clear felling, selective cutting or harvesting from plantations (Vos & Vis, 2010). Firstly, clear felling means clearing parts of a forest for other (often agricultural) purposes. Parts of the felled trees are used to produce charcoal. In exchange for clearing a part of the forest, the wood is often free of charge. Secondly, in case of selective cutting, trees with the best characteristics for charcoal production are chosen for felling. According to Vos and Vis (2010), these characteristics are generally large tree species (>20 cm diameter) in combination with a high caloric value. The first two harvesting types do not differ much in terms of the feedstock price, as in both cases the wood is obtained for free (Vos & Vis, 2010). Thirdly, the last type of harvesting is acquiring the wood from dedicated tree plantations. This is the preferred option when looking at sustainability; however, also the most expensive option compared to the other two harvesting types (Vos & Vis, 2010).

It is important to understand the difference between sustainable and unsustainable harvested biomass, or as mentioned before the difference between sustainable and unsustainable forestry. According to Ekeh et al (2014) biomass can be considered sustainable if "the land remains a forest" and "[...] the level of carbon stocks does not systematically decrease over time (stocks may temporarily decrease due to harvesting)" (p. 1644). According to Chidumayo and Gumbo (2013), the clearance of forests or woodlands for charcoal production can lead to deforestation.

In regions where hardwood is available in large amounts, the entire tree is usually harvested as fuelwood and used for charcoal production (European Commission, n.d.). However, the stems of trees are more valuable and therefore dedicated for the timber industry (Routa et al., 2011). For this reason in many other regions woody residues are used as biomass for wood energy as well as for charcoal production (Routa et al., 2011; Suopajärvi & Fabritius, 2013). As illustrated in Figure 5, woody residues for charcoal production is divided into three main categories: harvesting residues, industry residues and recycled wood (Suopajärvi & Fabritius, 2013). Harvesting residues include early thinnings, logging residues from final fellings and stumps of round wood harvesting. In addition, industry residues are also used and come in the form of bark, sawdust or industrial chips from round wood and pulpwood. Finally, recycled wood comes from the wood product market.

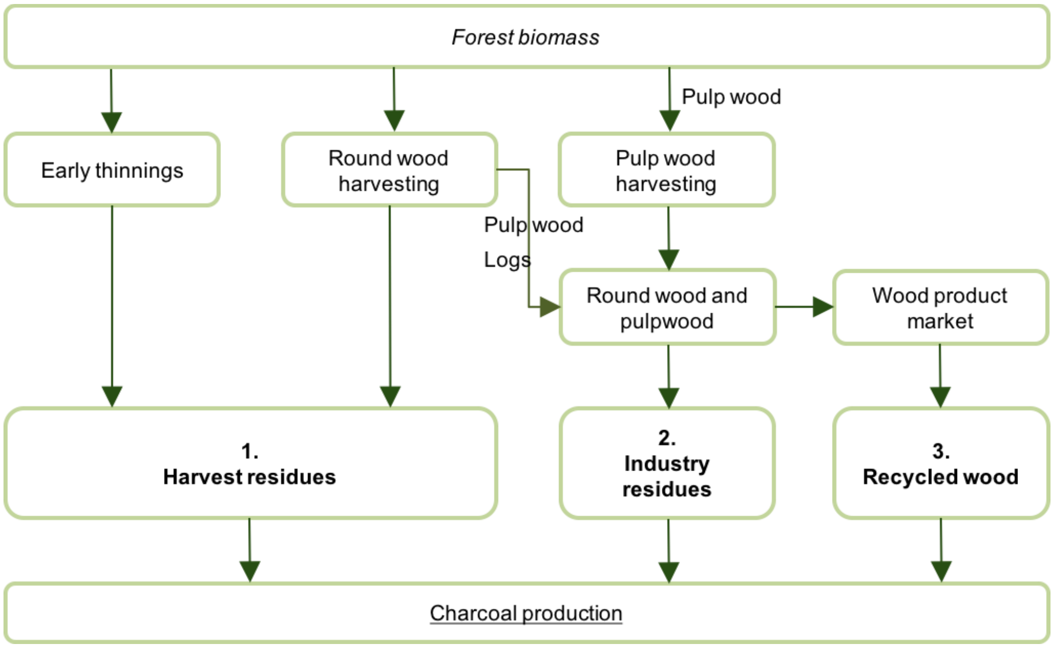

Figure 5. Origin of woody biomass for charcoal production adapted from Suopajärvi and Fabritius (2013).

After felling, the wood is <u>collected</u>. This can be either done by manpower or machines. Green biomass typically has a moisture content of around 50% - 60% wet basis throughout the seasons all over the world (FAO, 1985c; Krajnc, 2015; Svoboda et al., 2009). It is cheapest to reduce this moisture content by drying the wood in the open air in the sun, while it is covered against rain (FAO, 1985; Giuntoli et al., 2017). This is called <u>seasoning</u>. It is country dependent for how many months the wood can dry before intolerable biological deterioration occurs, such as insect attack or rotting (FAO, 1985). After seasoning, the lowest attainable moisture content is typically 18% - 20% (FAO, 1985). However, in most cases a moisture content of 30% is more realistic (Giuntoli et al., 2017). The loss in weight for drying is accompanied by an additional 5% dry matter loss due to biological deterioration (Giuntoli et al., 2017).

Then, the wood is processed (Kammen & Lew, 2005). In order to create a uniform carbonisation process, it is best that the feedstock has approximately the same size. The main types of processed wood for charcoal production are logs and chips (Lehmann et al., 2015). For logs the wood is sized into chunks of two metres long (Adeniji et al, 2015). Traditional kilns can only process logs, while industrial kilns can also process chips (Lehmann et al., 2015). Wood chips have a moisture content of around 30% (Krajnc, 2015). Processing usually takes place as close to the harvest place as possible in order to reduce additional emissions and intermediate transport costs, as processed biomass has an increased energy and volumetric density (Searcy et al., 2014). Finally, if needed, the processed wood is transported to the kiln, called intermediate transport.

2.3.3 Conversion

Woody biomass cannot carbonise until it is sufficiently dry. According to FAO (1985b) “[...] a lower moisture content contributes to a better thermal efficiency of the carbonisation process.” In addition to natural drying, seasoning, it is optional to dry the wood in an industrial process by dryers (Ogunsanwo et al., 2007). This is often the case with industrial production methods.[9]

Carbonisation is the conversion process for the production of charcoal (FAO, 1985). Two common carbonisation processes are slow and fast pyrolysis where slow pyrolysis produces the highest yield (Nsamba et al., 2015). Charcoal is the product left after biomass is burned at temperatures of about 350 - 550 °C and under the absence of oxygen (Ben-Iwo et al., 2016; Laird et al., 2009). Under these conditions, biomass will be broken down in volatile gases, vapour and solid char (Van Dam, 2017). “Efficiency of carbonisation is expressed as the yield of charcoal in gross terms (at the side of the retort or kiln) expressed as a percentage of the wood charged or used-up to produce it.” (FAO, 1985). The carbonisation efficiency is dependent on the wood species and the moisture content, but the type of kiln has the largest influence on the efficiency (Kammen & Lew, 2005). Charcoal can have a gross calorific value of up to 35 MJ/kg (Suopajärvi & Fabritius, 2013).

According to De Miranda et al. (2010) the various carbonisation methods are divided into four general type of kilns: the traditional, improved, semi-industrial and industrial kilns. Table 1 provides an overview of the different kiln types together with a rough estimation of their efficiencies

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[9] “Evaluation of a biomass drying process using waste heat from process industries: A case study” from Li et al. (2012) can be consulted to read more about biomass drying processes.

and the accompanied emissions.[10] Worldwide, traditional kilns are still used to produce charcoal, mainly in developing countries. In industrialized countries, modern technologies are introduced and replaced the traditional ones (Ogunsanwo et al., 2007). The principle of carbonisation is the same; however, modern conversion technologies have higher efficiencies and the released heat and by-products are internally used (FAO, 1985).

Table 1. Wood-to-charcoal efficiencies of various kiln types adapted from De Miranda et al. (2010).

Parameter	Unit	Value			
		Traditional	**Improved**	**Semi-industrial**	**Industrial**
Efficiency	%	8% - 12%	12% - 18%	18% - 24%	> 24%
Emissions	g/kg charcoal produced	CO_2: 450 – 550 CH_4: ~700 CO: 450 - 650			CO_2: ~400 CH_4: ~50 CO: ~160

The two most often occurring traditional kilns are the earth-mound kiln and earth pit kiln. These traditional technologies have already been used for many years and the method has not changed much. Woody biomass is the only raw material that can be used as other materials would catch fire. Both methods involve stacking wood and covering it with earth, grass, mud or soil (Stassen, 2015). Small holes are made to let steam and smoke escape. The wood is then ignited to start the carbonisation process. Incomplete combustion occurs, resulting in GHG emissions with a higher GWP than CO_2, such as methane and other non-methane volatile organic substances (Ekeh et al., 2014; Kituyi, 2004). Another disadvantage is the low efficiency (Stassen, 2015). On the other hand, this method has very low investment costs and requires minimal wood preparation. Nowadays, traditional kilns are still used in many developing countries. It is also the main production method in Sub-Saharan Africa (Chidumayo & Gumbo, 2013).

Examples of improved kilns are: Casamance kilns, Missouri kilns, Argentine kilns and the Brazilian Beehive kilns (FAO, 2008; Stassen, 2015). Among these kilns there are large differences; in some cases, the principle of traditional kilns has been improved, while in other cases the kilns have a completely new design, now constructed of brick or steel (Stassen, 2015). These improved kilns enable air-flow regulation. This makes it possible to use other biomass than wood as input, such as agricultural residues. Improved kilns have a higher yield and production

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[10] For further reading about traditional production Foley's (1986) article “Charcoal making in developing countries” is recommended. More information on the efficiencies of different kilns can be found in *The Charcoal Transition* (Van Dam, 2017).

efficiency than the traditional kilns, that require bigger investments and construction is more complicated (FAO, 1985).

In semi-industrial kilns the produced gases are led back into the carbonisation compartment. Therefore, a bigger part of the tar components is combusted and the kiln reuses the heat of the emitted gases (Girard, 2002). These modifications improve the efficiency of the method, resulting in less volatile organic carbon emissions to the air compared to previous techniques. Semi-industrial kilns are stationary resulting in higher costs for intermediate feedstock transportation (Seidel, 2008). Semi-industrial charcoal kilns have a shorter production cycle, in comparison to previously mentioned kilns.

Industrial kilns are more complex (Stassen, 2015). The added complexity comes with advantages; these kilns are the most efficient ones, resulting in higher charcoal yields compared to all the other kilns. When woody biomass is used as feedstock the charcoal yield with slow pyrolysis is between 25% - 35% mass basis (Nsamba et al., 2015; Suopajärvi & Fabritius, 2013). Despite the quick carbonisation process, industrial methods require significant investments and higher wood preparation costs. The wood has to be dried well upfront and afterwards it has to be cut into (small pieces) of roughly the same size (Stassen, 2015). Therefore, more advanced production methods require an improved infrastructure further increasing costs (Stassen, 2015). Due to these high costs, industrial kilns are mostly used in industrialised countries.

Despite the fact that an attempt has been made to introduce more efficient technologies in developing countries, there are multiple reasons why these efficient kilns are not widely adopted. According to (Van Dam, 2017), one of the reasons for these countries to reject more efficient kilns is their lack of mobility, since there is a demand for the charcoal kilns to be moved to the location of wood harvesting. Moreover, for the newer technologies more expertise on construction and production is necessary, skills that are not always available. Additionally, investment costs are excessively high for newer technologies and cannot be afforded. These are all factors that give an advantage to the traditional, less efficient, low-investment kilns. Finally, charcoal obtained through illegal practices result in lower charcoal price. According to Vos and Vis (2010), the charcoal sector in a country could be (partly) illegal when "[…] production, trade, or consumption has been declared illegal" (p. 43), or the feedstock is obtained illegally. Therefore, legally produced charcoal generally cannot compete with charcoal obtained from a partly illegal charcoal sector. More expensive technologies cannot be recouped, since this charcoal will not be sold.

2.3.4 Distribution logistics

The distribution logistics consist of packaging and transportation. After production, the charcoal is packed and transported to wholesalers, retailers or in some cases directly to the consumer.

The three main transportation modes used for biomass are by road, rail and water (maritime and inland) (Giuntoli et al., 2017). Which transportation mode is used depends not only on the distance, but also on the availability of transportation modes as well as the presence and quality of the infrastructure (Vos & Vis, 2010). For all transportation modes, the return trip should be taken into account (Giuntoli et al., 2017). It should be considered if the return trip is empty, partially loaded, or fully loaded (Giuntoli et al., 2017). The transport of the charcoal also involves GHG emissions due to the combustion of fuel in transportation vehicles (Ekeh et al., 2014). The mode of transportation significantly affects the amount of GHG emissions (Benjaafar et al., 2013). Additionally, the costs related to the type of transport play a large role (Vos & Vis, 2010). Transportation can account for up to 25% of the total production costs (FAO, 1987).

There are several ways charcoal is packed, but often it is transported in bulk (Cargo Handbook, 2016). Most often, domestic bulk transport for relative short distances is done with trucks (Giuntoli et al., 2017). However, traditional producers do not find bulk transportation practical and package their charcoal in bags (FAO, 1987). Charcoal dust and fines are created foremost in loading and unloading operations. To minimize charcoal loss, it is advisable to transport the charcoal from kiln to distribution or storage point in one go (FAO, 1987). Most truckers transport the charcoal in burlap bags. General purpose trucks are suited to carry these bags, so they can carry other material on their return trip. Bagged charcoal takes about 2% - 5% more space to pack than loose charcoal (FAO, 1987).

When charcoal is exported out of a country over larger distances, generally, it is shipped. For maritime transport, there are various types of sea bulk carriers with different sizes and container ships (Giuntoli et al., 2017). A major barrier to maritime transport are the shipping costs. These costs are dependent on several factors such as: demand for shipping, port efficiency, and the typical feature of the feedstock (Searcy et al., 2014). Larger ships carry the benefit of economies of scale, resulting in reduction in costs as well as GHG emissions (Lindstad et al., 2012). Inland charcoal transport to and from the port mostly take place by truck or train. During loading and unloading in the transportation stage, charcoal losses occur and less charcoal reaches the end-user (Van Dam, 2017). These losses indirectly cause higher GHG emissions in the entire supply chain.

2.3.5 End-use

Finally, the charcoal reaches the end-user or consumer. Emrich (1985) distinguishes two different consumer markets, namely households and industries. Households use charcoal for cooking. In the urban areas of developing countries charcoal is often the only option for relatively clean cooking fuel (Van Dam, 2017). In industrialised countries charcoal is used for barbecuing as leisure activity (Johnson, 2009). The final quality of charcoal is dependent on the type of wood, the moisture content of the wood, and on the type of carbonisation method used (Van Dam, 2017). For households in developing countries, the quality of charcoal is of less importance than for households in industrialised countries (Emrich, 1985).

Within various industries there is a wide range of applications for charcoal according to Tran et al. (2017), such as: "[...] direct combustion of charcoal as solid fuel, gasification of charcoal for synthesis gas production, and use as reductant alternative to fossil carbon in metallurgical industry." (p. 787). As early as the Middle Ages charcoal has been used as a reducing agent, however, over the years charcoal is replaced by coal in the metal manufacturing industry (Van Wesenbeeck et al., 2016). Nowadays, the charcoal demand is on the rise again, since "[…] countries such as Malaysia, Brazil, Argentina, and recently, Norway (specifically its major ferrosilicon industry) use charcoal as a reductant" (Van Wesenbeeck et al., 2016, p. 7959). Charcoal from softwood product is not adequate as industrial charcoal (FAO, 1985).

3. Case study

This chapter describes the application of the charcoal supply chain to the two cases applied in this research: the “as-is” case where charcoal is produced in Nigeria, *Scenario NG*, and the case where charcoal is sustainably produced within the EU, *Scenario EU*. In both scenarios, the produced charcoal is transported to and consumed in the Netherlands. *Scenario NG* describes the current situation in Nigeria as close as possible to reality. *Scenario EU* considers state-of-the-art sustainable charcoal production in the EU, specifically Finland.

3.1 Scenario Nigeria

For *Scenario NG*, first, some background information regarding the Nigerian charcoal sector is given. Afterwards, the five stages and the relating activities of the charcoal supply chain for *Scenario NG* are discussed.

3.1.1 Nigerian charcoal sector

In Nigeria there is an enormous energy shortage (Nwofe, 2013). Less than half of the population has access to electricity and is connected to the national grid (Gujba et al., 2015). In the rural areas only 10% has this access (Gujba et al., 2015). Other energy sources such as liquefied petroleum gas and kerosene are often too expensive for many inhabitants (Gujba et al., 2015). In the past years, there is an increasing demand for traditional biomass as fuel due to the kerosene scarcity and its high prices (Elijah et al., 2017; Nwofe, 2013).

Charcoal is a popular energy source because of the abundant availability, absence of smoke compared to fuelwood, and its relatively low price (Elijah et al., 2017). In Nigeria, charcoal is an important energy source within the traditional biomass options, mainly used for cooking (Elijah et al., 2017; Nwofe, 2013). According to Nwofe (2013), charcoal accounted for 31% of all cooking sources. Charcoal is energy denser than fuelwood and therefore easier to transport and store (Elijah et al., 2017). Charcoal is more commonly used in urban areas, mainly by the low and middle income households (Elijah et al., 2017; Nwofe, 2013). For the rural households’ fuelwood is still the dominant energy source (Nwofe, 2013).

Nigeria is the largest charcoal producer of Africa (Daramola & Ayeni, 2016). However, the production activities in Nigeria are informal, secretive and documentation is lacking (Daramola &

Ayeni, 2016). According to Vos and Vis (2010), this is often a result of an unregulated and partly illegal charcoal sector. Babalola and Opii (2012) state a number of problems regarding the charcoal sector in Africa: unclear policies, lack of sustainable raw materials and inefficient production, no standards and corruption. These problems are also recognised in Nigeria and explained below.

The first problem is related to unclear policies and legislation (Babalola & Opii, 2012). In 2016, there was a ban on charcoal export by the Nigerian federal government. The ban had arisen because the agreements on tree planting were not met, the so-called cut-one plant-two policy (Oritse, 2016). Later that year the ban was lifted again (Johnson, 2016). “The problem is complicated because the federal government owns the policy and the machinery to enforce the law, but the states own the forest” (Goswami, 2018).

Secondly, there is a lack of sustainable wood production, resulting in exploitation of current wood stocks (Babalola & Opii, 2012). From an environmental perspective, it is best to produce charcoal with wood from dedicated tree plantations (Babalola & Opii, 2012). However, in Nigeria a lot of illegal logging occurs, where trees are not replanted (Jamala et al., 2013). Therefore, charcoal production affects vegetation and leads to the destruction of forests, resulting in negative impacts for the environment (Elijah et al., 2017; Jamala et al., 2013; Nwofe, 2013). Whether charcoal production ultimately leads to deforestation is ambiguously reflected in different articles. However, according to Chidumayo and Gumbo (2013) in the world, Nigeria was third in terms of actual forest cover loss, with almost 30% due to charcoal production (Figure 6). Nigeria is one of the countries with the highest loss of forests and woodlands (Daramola & Ayeni, 2016). Between 1990 and 2010 the amount of forest cover in Nigeria was almost halved (Fadare, 2017). At the moment, the deforestation rate is approximately 3% per year, resulting in an annual loss of around 410,000 hectares (Gujba et al., 2015). In Nigeria, deforestation together with the burning of fossil fuels are the biggest contributors to the GHG emissions (Fadare, 2017).

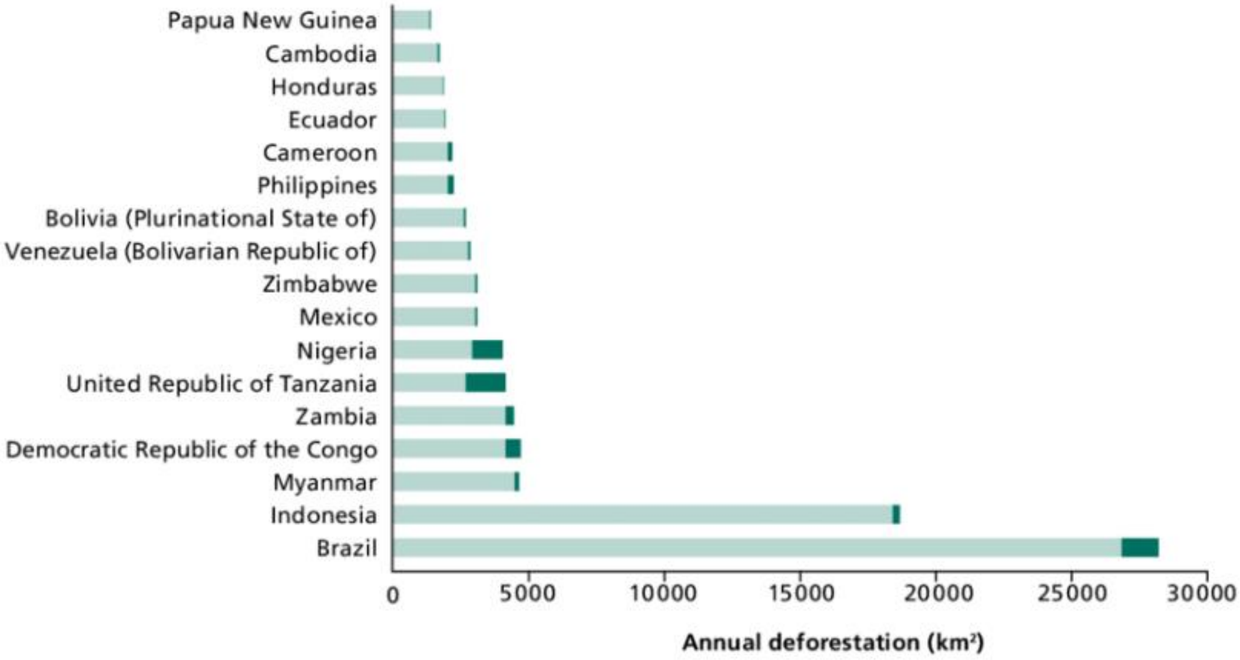

Figure 6. Deforestation caused by charcoal production (dark green bars) and deforestation caused by other factors (light green bars) in 2009 (Chidumayo and Gumbo, 2013).

Another problem is the inefficiency of the currently still used traditional charcoal production methods (Babalola & Opii, 2012). Since the traditional conversion stage is an emission and feedstock intensive step in the charcoal supply chain (FAO, 1985), an efficient technology is essential in order to increase yields and reduce the amount of woody biomass input. In Nigeria, the majority of charcoal is carbonised in traditional earth kilns (Adeniji et al, 2015).

Lastly, the unregulated and partly illegal charcoal sector is often accompanied by corruption (Vos & Vis, 2010). It is estimated that in Africa various terrorist groups earn around 289 M$ from illegal charcoal trade per year (UNEP, 2015). Between 2007 and 2011, the Nigerian federal government has lost over 2.4 M€ to illegal charcoal export towards Europe and the Middle-East (Abutu, 2011). It is unclear from this newspaper article what the nature is of this loss. An explanation for this, according to Babalola and Opii (2012), could be the missing tax revenues: “[…] the taxman is permanently locked out of these transactions as most are done on an ‘underground’ basis” (p. 78).

Figure 7 illustrates the charcoal supply chain and its associated activities for *Scenario NG*. The rest of this section elaborates on these stages.

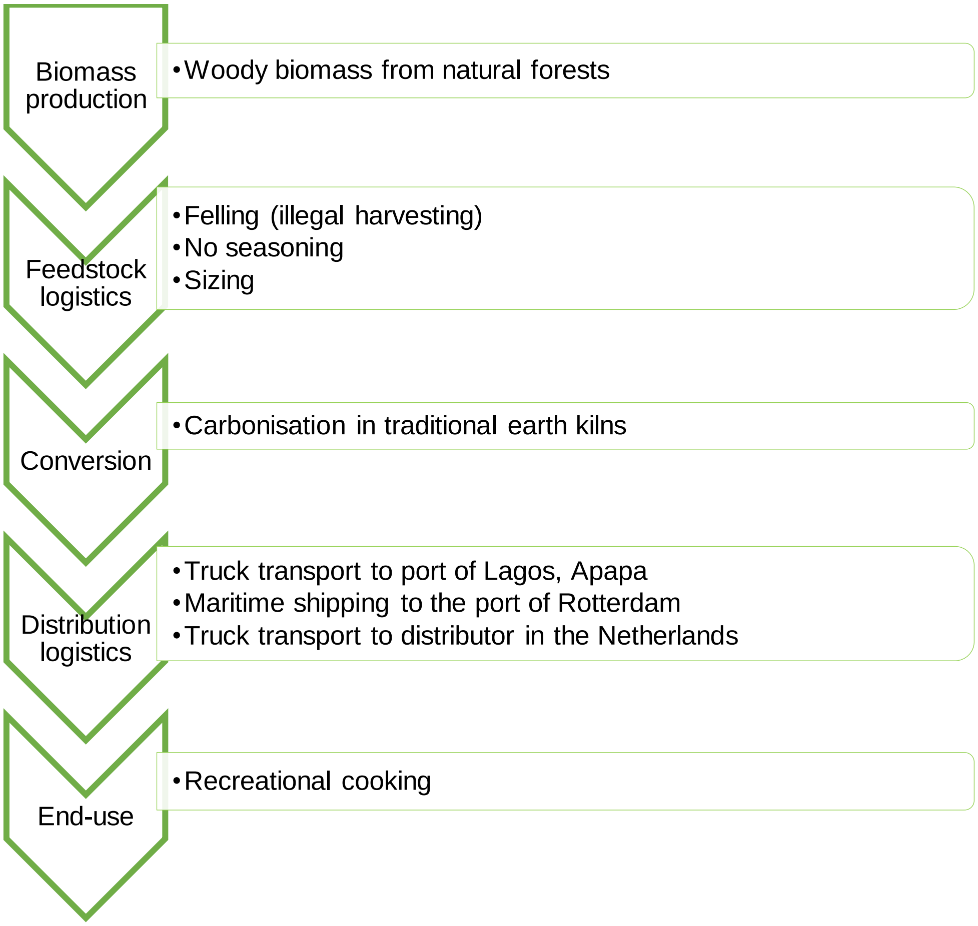

Figure 7. Charcoal supply chain *Scenario NG.*

3.1.2 Biomass production

In Nigeria, charcoal production almost completely depends on natural forests (Jamala et al., 2013). This is common for tropical countries in SSA, despite increasing investments in forest plantations (Chidumayo & Gumbo, 2013). In literature, only one Nigerian charcoal producer was found that used tree residues from a plantation (Adewole & Oladejo, 2016). Therefore, it is assumed that the woody biomass for charcoal production in Nigeria is selectively cut from natural forests. As mentioned before, silviculture is not considered when hardwood originates from unmanaged natural forests (Daystar et al., 2013).

In Nigeria, hardwood is used for charcoal production (Adeniji et al, 2015). According to Adeniji et al (2015), in the Borgu Local Government Area of Niger State the most preferred tree species for charcoal production is Prosopis Africana, followed by Anogeissus Leiocarpus. Ogunsanwo et al. (2007) found that Anogeissus Leiocarpus was the most preferred tree species in Oyo State, probably due to having the highest calorific value. Within this research woody biomass from

Anogeissus Leiocarpus is assumed as raw material, also known as African Birch (Bello & Jimoh, 2018).

3.1.3 Feedstock logistics

Acquiring wood in Nigeria is in most cases free of charge for charcoal producers as this wood comes from natural forests (Fadare, 2017). The problem of free access to wood resources is that producers do not feel the urge of replanting trees (Adeniji et al, 2015). Therefore, wood is often harvested unsustainably leading to forest degradation or even deforestation. According to the case study of Adeniji et al. (2015), only 24% of the charcoal producers replant trees after harvesting the wood for charcoal production. However, a recent newspaper article states: "[...] that all those that are producing and exporting charcoal failed to plant another tree, a situation that has created the depletion of the forest." (Fadare, 2017).

(Tropical) forests typically contain large amounts of biomass both above- and below ground and thus can be seen as enormous carbon pools, absorbing CO_2 from the atmosphere (Adeniji et al., 2015; Eneji et al., 2014). In Nigeria, most charcoal producers harvest unsustainably; therefore, charcoal production results in net CO_2 emissions (Ekeh et al., 2014).

In Nigeria, trees are mostly felled by using a chainsaw, and only in some cases with a cutlass (Adeniji et al, 2015). It is best to season the wood before carbonisation in order to get a higher yield; however, Fadare (2017) found at Kwara State that trees were not seasoned before carbonisation, indicating that wet wood is put into the kiln.[11] It is assumed that sizing is done by using the same chainsaw as for felling. When using traditional production methods, carbonisation often takes place near the harvesting site (Chidumayo & Gumbo, 2013; Van Dam, 2017); therefore, no additional intermediate feedstock transport is needed within Nigeria.

3.1.4 Conversion

In Nigeria, the majority of charcoal is carbonised in traditional earth kilns (Adeniji et al, 2015). According to Adeniji et al (2015), 65% of the time the earth-mound kiln is used in the studied area, while 35% of the time the earth pith kiln is used. The main difference between the two methods is that the earth-mound kiln is constructed on the ground, while the earth pit kiln by digging a pit into the ground (Adeniji et al., 2015; Chidumayo & Gumbo, 2013), see Figure 8. According to Chidumayo and Gumbo (2013) the average conversion efficiency of the earth-mound kiln and

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[11] This is also mentioned in the article by Luoga et al. (2000), however, note that this article is about Tanzania.

earth pit kiln in tropical regions are 25.7% and 11.8% respectively. Other research finds similar efficiencies for these methods (Van Dam, 2017). In Nigeria, industrialised kilns are not used due to the higher expenses (Adeniji et al., 2015). Moreover, woody biomass is freely available and therefore, charcoal producers do not feel the urge to seek the most efficient production method, rather the cheapest. As mentioned in the previous step, the moisture content of the wood is not reduced by means of seasoning before carbonisation. The moisture in the wood first has to be evaporated during the carbonisation process in order to carbonise the wood. This contributes to a lower charcoal yield than bone-dry wood would have (FAO, 1985). To turn the woody biomass into charcoal takes about two weeks (Aiyeloja & Chima, 2011).

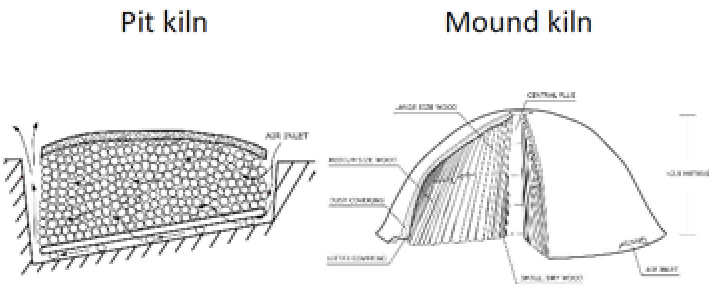

Figure 8. Earth pit kiln and earth-mound kiln (International Biochar Initiative, 2018).

3.1.5 Distribution logistics

In Nigeria, the charcoal is bagged after carbonisation. Afterwards, it is sold to merchants who take the charcoal to urban centred selling points, or directly to individuals who consume it (Adeniji et al., 2015). There are numerous places in Nigeria where charcoal is available as many local communities have developed their charcoal production (Adeniji et al, 2015). Charcoal depots are found at the following places: “[...] Oyo, Iseyin, Saki, Igbo-Ora, Ogbomoso- all in the western part of the country. There are also depots in Jebba, Omu Aran, Egbe, Kabba in the Central States. Finally, charcoal is found in abundance in Minna, Jos and Kaduna.” (Adeniji et al, 2015, p.1).

According to Daramola and Ayeni (2016), charcoal transportation from the production sites happens by pick-up trucks, followed by mini trucks. Only a minor part is transported with a container truck.

The charcoal destined for export is transported from Oyo state to the port of Lagos (Fadare, 2017). This port, named Apapa port complex, is the biggest port in Nigeria and handles half of the total maritime trade of the country (Buhari, 2013). Afterwards the charcoal is transported to the EU, specifically to the Netherlands. The largest port of Europe in terms of container throughput is located in Rotterdam, the Netherlands, an important distribution point and considered as the import harbour within this research (Notteboom, 2010). According to Jamala et al. (2013), from Nigeria charcoal is transported in containers. From the port of Rotterdam, the charcoal is transported by truck towards the distribution centres.

3.1.6 End-use

For both scenarios, it is assumed that the charcoal is consumed for barbecuing within the EU. For both scenarios, it is assumed that the produced charcoal has a lower heating value [LHV] of 30 MJ/kg (Abasiryu et al., 2016). The transportation part from the place of purchase to the consumer is neglected.

3.2 Scenario European Union

First, some background information is given about the current charcoal sector in the European Union. Then, this section discusses the charcoal supply chain of *Scenario EU.*

3.2.1 Charcoal in the European Union

Within this research, state-of-the-art sustainable charcoal production is assumed for *Scenario EU*. In reality the charcoal production of the EU has slowly decreased over the last decade[12], as can be seen in Figure 9.

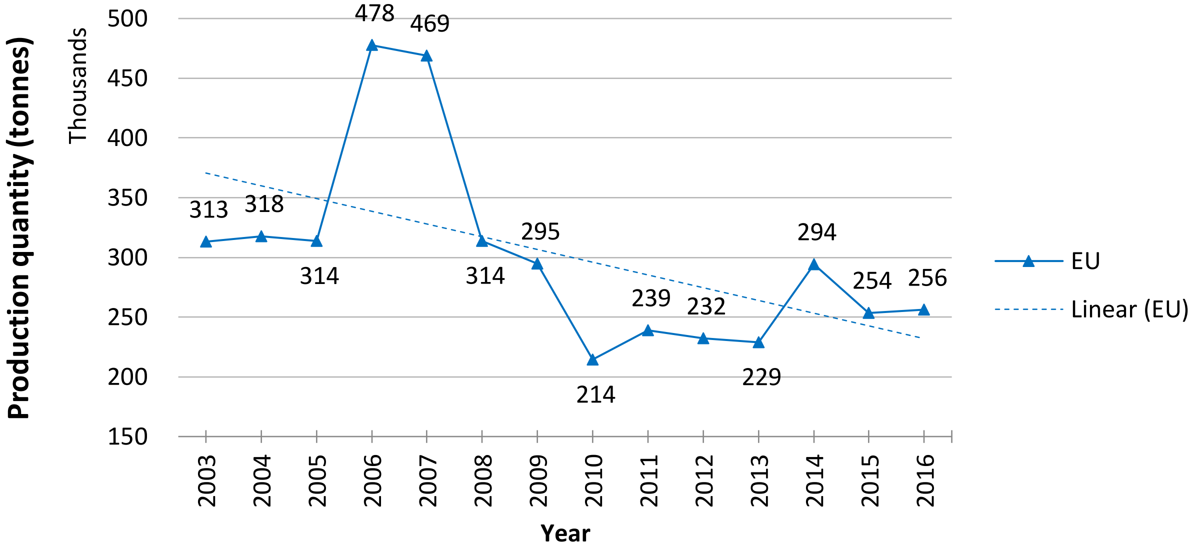

Figure 9. Charcoal production in the EU (FAOstat, 2017).

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[12] While this is an interesting trend, the reasons for this decrease is outside the scope of this research,

It is important to note that not all countries in the EU produce charcoal as sustainably. Poland for example, is the biggest producer within the EU, with an annual production of around 100 ktonnes (FAO Statistics, 2017). However, charcoal from Poland could be problematic, since in the recent past bags with charcoal from Poland contained tropical woods (Hilse, 2017). Multiple sources imply that within the EU, FSC-certified charcoal is sold containing illegally harvested timber (Crumley, 2017; Hilse, 2017). When this is the case, first, the charcoal is imported form a country without FSC-certified forests. Then, in the EU it is repacked and sometimes mixed. Finally, it is sold as FSC-certified charcoal produced within the EU. This is also occurring in Poland (Hilse, 2017). Moreover, in Spain, another large charcoal producer and exporter in the EU, "[…] most of the biochar is produced using traditional low cost batch technologies such as earth mounds kilns, metal ring kilns and Missouri type kilns." (San Miguel et al., 2017, p. 1). Therefore, Polish charcoal and Spanish production conditions are not assumed in this scenario.

Finland is a more suited country, as it is the most forested land within the EU, where forests cover three quarters of the land area (Finnish Forest Association, 2014). Finland is very far in the field of forestry and already produces charcoal for sustainable ironmaking: *Towards More Sustainable Ironmaking—An Analysis of Energy Wood Availability in Finland and the Economics of Charcoal Production* from Suopajärvi and Fabritius (2013). Therefore, Finnish conditions are chosen as representative for sustainable charcoal production within *Scenario EU*.

Figure 10 illustrates the charcoal supply chain and its associated activities. The rest of this section elaborates on the charcoal supply chain of *Scenario EU*.

3.2.2 Biomass production

In the EU, charcoal is generally obtained from tree species such as Beech, Hornbeam, Oak, Adler or Birch due to their high calorific value (Samojlik et al., 2013). Since Silver Birch is one of the most available tree species in Finland, therefore this species is considered in this scenario(Natural Resources Institute Finland, 2016). In large industrial plantations within the EU, biomass for energy predominantly results from by-products and residues (Akyüz & Balaban, 2011). This woody biomass can be produced sustainably in large amounts in northern Europe in controlled and maintained forests and fast-growing plantations (Mola-Yudego et al., 2017). In Finland, most forest biomass consumed to produce energy, also called energy wood, comes from harvest residues and stumps (Routa et al., 2013). Therefore, this scenario assumes that harvest residues from Finland are used as feedstock. Harvest residues therefore are not considered as waste and silviculture is considered as a part of *Scenario EU's* charcoal supply chain (Leinonen, 2004).

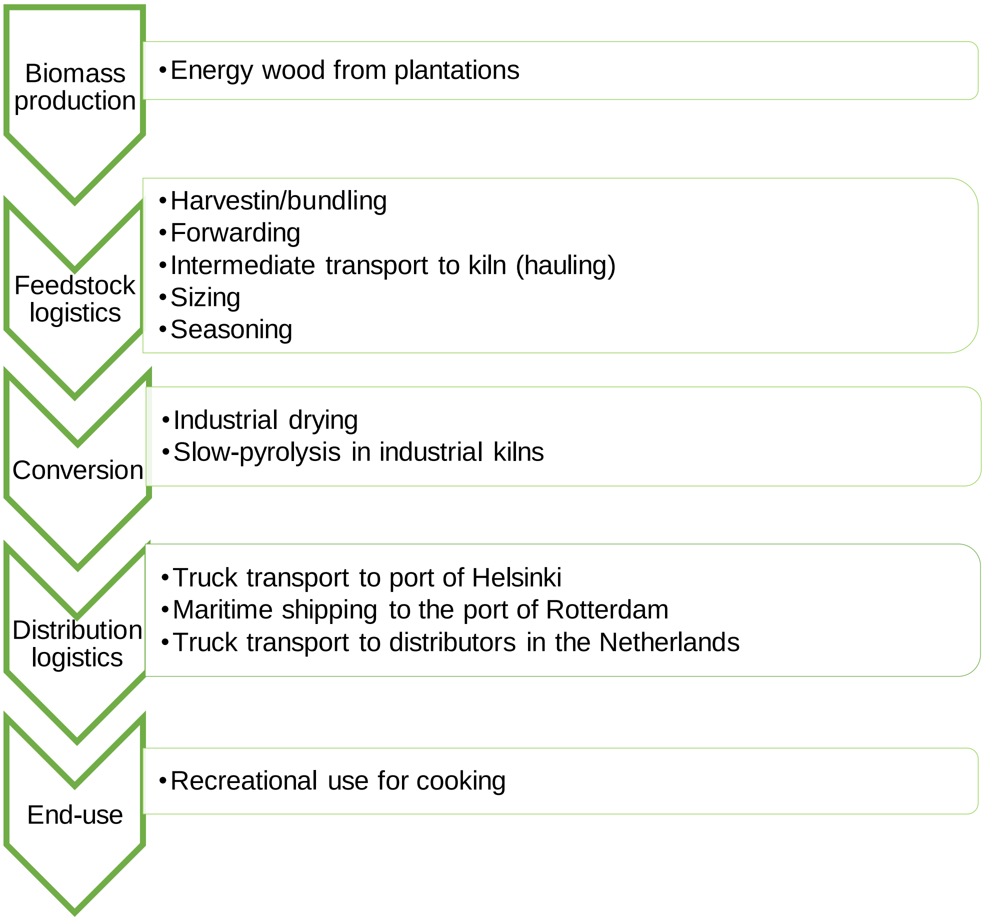

Figure 10. Charcoal supply chain *Scenario EU.*

3.2.3 Feedstock logistics

After the energy wood is harvested, the wood is bundled and transported to the forest-end by a forwarder (Valente et al., 2012). In Finland, trucks are the dominating transportation mode for transporting energy wood bundles from the harvesting site to production plants (Tahvanainen & Anttila, 2011). This intermediate transport is also referred to as hauling. In this scenario, it is assumed charcoal is produced using the Twin-retort system, a state-of-the-art charcoal production method.[13] Before the residues are processed, they are appropriately sized (Reumerman & Frederiks, 2002). Finally, seasoning occurs at the conversion site and the woody biomass is air-dried during storage.

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[13] For a more elaborate explanation of the Twin-retort system, please refer to Reumerman and Frederiks (2002).

3.2.4 Conversion

Table 2 displays the output yields for different pyrolysis conversion modes. This research assumes slow-pyrolysis as it results in the highest charcoal yield. Slow-pyrolysis results primarily in charcoal and syngas, dependant on the input (Brown et al., 2011; Duku et al., 2011; Roberts et al., 2010). Figure 11 displays the typical slow-pyrolysis process, taken from Duku et al. (2011).

Table 2. Product yields obtained from wood by different modes of pyrolysis adapted from Duku et al. (2011).

Mode	Temperature	Residence time	Liquid (bio-oil)	Solid (char)	Gas (syngas)
Fast pyrolysis	Moderate temperature (~500)	Short vapour residence time (<2s)	0.75	0.12	0.13
Slow-pyrolysis	Low-moderate temperature	Long residence time	0.30	0.35	0.35
Gasification	High temperature (>800)	Long vapour residence time	0.05 tar	0.10	0.85

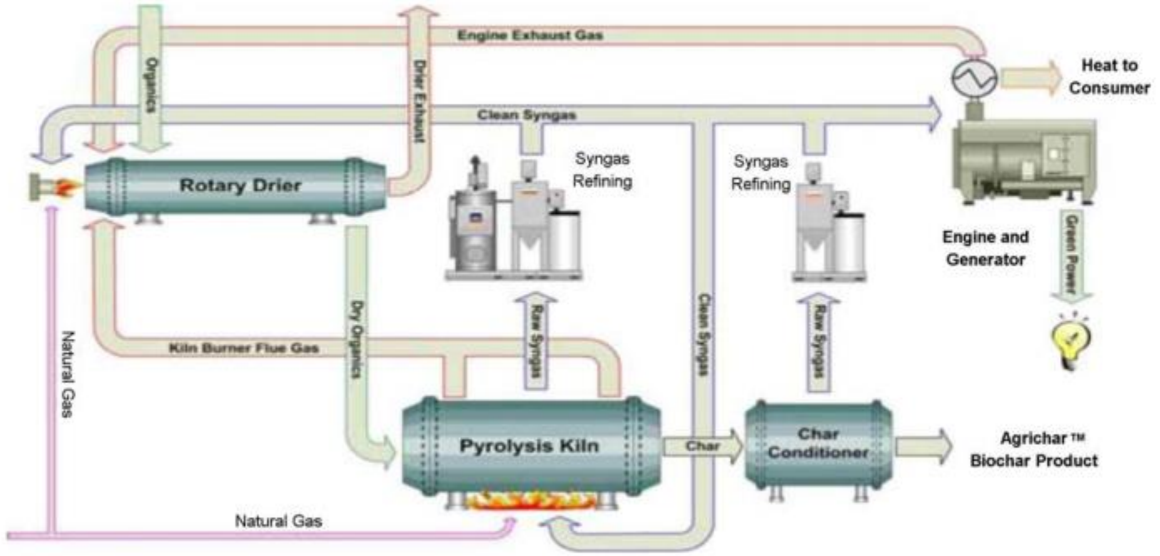

Figure 11. Slow-pyrolysis process (Duku et al., 2011).

The Twin-retort system is a retort reactor type where a slow-pyrolysis process carbonises the woody biomass. The off-gases of the carbonisation process are internally used to dry the wood to an acceptable moisture content level of below 20% (Klavina et al., 2016; Reumerman & Frederiks, 2002). In addition to the syngas, additional fossil fuels are needed to provide enough heat.

3.2.5 Distribution logistics

After the charcoal is produced at the plant, it needs to be transported to the port of Rotterdam. As Eriksson (2008) found in her study on transportation systems from Scandinavia to the

Netherlands, woody biomass is generally transported by truck to a major harbour before being transported by a Handymax-sized ship to Rotterdam. The charcoal is thus assumed to be transported by truck to the port of Helsinki. As in *Scenario NG* this report assumes the charcoal is shipped in containers and not on a bulk-carrier ship. In the port of Rotterdam, the charcoal is unloaded and transported to distributors. According to Giuntoli et al. (2017), the typical distance in the EU for charcoal road transport is 50 km. This distance is therefore assumed as the average distance the charcoal is transported in the Netherlands to distributors. In this scenario, the transport from distributor to retailers and from retailers to end-consumers is considered negligible.

3.2.6 End-use

As well as in *Scenario NG*, for this scenario is assumed that the charcoal is used for barbecuing. The produced charcoal has an LHV of 30 MJ/kg (Abasiryu et al., 2016).

4. Methodology

This methodology chapter first covers the overall research design, how the results from the analyses are interpreted to answer the research questions. Then, the three analyses are operationalised, consisting of data collection and data analysis. Finally, a combined sensitivity and uncertainty analysis is discussed for the LCA and EA.

4.1 Research design

The goal of this research, as reflected in the research questions, is to quantify the impact in terms of greenhouse gas emissions and monetary value of shifting the EU's charcoal import from Nigeria to sustainably produced charcoal in the EU. In order to do this, three analyses are conducted on two scenarios (Table 3).

Table 3. Overview of the research design.

Analysis	*Scenario NG*	*Scenario EU*	Comparison
Trade database comparison	EU's charcoal import from Nigeria	EU's charcoal import from the EU	EU's import prices
Life cycle assessment	GWP *Scenario NG*	GWP *Scenario EU*	Difference in GWP
Economic analysis	Costs and benefits *Scenario NG*	Costs and benefits *Scenario EU*	Difference in costs and benefits

The scenarios are elaborated on in the previous "Case study" chapter, where the charcoal supply chain is applied to both scenarios. *Scenario NG* describes the current situation in Nigeria as close as possible to reality and *Scenario EU* considers state-of-the-art sustainable charcoal production in the EU. The data on the charcoal supply chains is collected via desk research and serves as a foundation for the LCA and EA.

Three types of analyses are executed within this research: a trade database comparison, a single impact LCA, known as carbon footprinting, and an EA. The trade database comparison examines three different trade databases to map the EU's charcoal import, both in terms of quantity and monetary value. The charcoal trade is mapped to get a better understanding of the current situation and the recent past. The LCA and EA are conducted in parallel for both *Scenario NG* and *Scenario EU*. The LCA consists of the goal and scope definition, inventory analysis, impact assessment and interpretation. This analysis calculates the GWP of the charcoal supply chain for both scenarios. The EA consists of preparation, technology characterisation and the cost-benefit analysis. This analysis examines the charcoal production costs and benefits for both scenarios, and calculates their NPVs.

After the analyses are executed, the results have to be interpreted. To answer the first research question, first, its sub-questions must be answered. For answering sub-question 1a the EU's import quantity from Nigeria is derived from the TDC. Then, the GWP for *Scenario NG* is calculated by conducting the LCA and together with the import quantity from 1a, sub-question 1b is answered. Finally, to answer sub-question 1c, the GWP of *Scenario EU* is estimated in a similar matter and compared with the GWP of *Scenario NG*. By combining the answers of these three sub-questions, the first main research question is answered, resulting in the potential mitigation that can be achieved by producing the amount of currently imported Nigerian charcoal sustainably in the EU instead.

To answer the second research question, again, its three sub-questions need to be answered. Sub-question 2a examines the difference in the EU's import price for charcoal from Nigeria and the intra-EU import price. This is done by dividing the monetary value of the import by the quantity, derived from the TDC. Secondly, sub-question 2b will provide insight into the production costs associated with the charcoal produced in both scenarios by conducting an EA, specifically a cost-benefit analysis will specify the NPV. Sub-question 2c explores possible policy implementations aimed to reduce EU's charcoal import from unsustainable sources. The combination of these sub-questions, again, answers the second main research question. Namely, the feasibility of shifting the EU's charcoal import from Nigerian charcoal to sustainably produced charcoal in the EU.

The next sections elaborate on the three analyses and explain the operationalisation per analysis.

4.2 Trade database comparison

To map the current EU's charcoal import, this research compares three online trade databases. First, the need for a comparison between multiple databases is explained. Then, the details of the three databases are discussed. Finally, data preparation is explained, so the trade databases can be compared against one another.

4.2.1 Database reliability

Multiple databases are consulted since there is a scarcity of accurate statistics on trade flows within the charcoal sector (Serrano-Medrano et al., 2014). Various determinants influence this lack of data, such as illegal production, which is caused by the unregulated and informal characteristics of the charcoal sector in most countries (Mwampamba et al., 2013; Serrano-

Medrano et al., 2014). In addition, charcoal production involves many rural producers separate from each other and therefore production is dispersed (Mwampamba et al., 2013). Moreover, consumption often takes place in rural areas and never even enters the formal market (Serrano-Medrano et al., 2014). Still, there are databases available that are constructed using multiple sources for information in combination with experts' estimations (Mwampamba et al., 2013). Within these databases, approximate calculations of production, consumption and trade numbers are often used when data is absent. This could result in differences between reality and reported data (Mwampamba et al., 2013). Charcoal trade statistics are thus often incomplete or unreliable. Therefore, multiple trade databases have been consulted.

4.2.2 Database description

The three databases compared in this research are from the following organisations: European Commission [EC], International Trade Centre [ITC] and Food and Agriculture Organization of the United Nations Statistics [FAOstat] (Table 4). First, the definitions of charcoal according to the three databases are compared. To characterize products internationally, the HS 2012 six-digit product code is used as a standard (United Nations Statistics Division, 2013). This research will only focus on wood charcoal as other definitions of charcoal fall outside the scope of this research.[14] The definitions of wood charcoal do not vary substantially between the three databases; therefore, these databases are comparable on their data on wood charcoal. Next, the specificity of the data is checked. The EC and ITC databases provide the origin of EU's charcoal import, so with these databases the amount of Nigerian charcoal imported by the EU can be found. The FAO database, however, does not specify the origin of the EU's charcoal import and therefore this database cannot be used to find the amount of Nigerian charcoal imported by the EU. All three databases present the total EU's charcoal import from the world. However, the ITC and FAO database include intra-EU charcoal trade (charcoal which is traded among the EU Member States), while the EC database excludes intra-EU trade (only considers trade between the EU and non-EU Member States). Finally, the availability of historical data is considered, the corresponding time period between the three databases is from 2003 up to and including 2016. Appendix A elaborates in more detail how the exact same data per database can be obtained.

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[14] For wood charcoal the code is 4402, consisting of three sub categories: 4402.00, 4402.90 and 4402.10. The difference between 4402.00 and 4402.90 is that bamboo charcoal is included within 4402.00 and excluded in 4402.90.

Table 4. EC, ITC and FAO trade database details.

Trade database	Product code	Importing country/region	Exporting country/region	Data availability	Trade detail
EC	4402	EU28	All partners; Nigeria	2003-2017	Extra-EU trade
ITC	4402	EU28	All; Nigeria	2001-2017	Including intra-EU trade
FAO	4402.90	EU28; Nigeria	World	1961-2016	Including intra-EU trade

4.2.3 Quantities and monetary values

The results of this analysis are the EU's charcoal import in quantity and monetary value from the world, extra-EU, intra-EU and Nigeria. Eventually, the EU's import price for charcoal per quantity can be approximated for these regions.

Within this research, the EU indicates the 28 Member States and the EU's import is the sum of each of these countries. As mentioned before, the EU's charcoal import is explored for four specific regions. Namely, the charcoal import from the world, reflecting the global trade to the EU. Secondly, the EU's import from extra-EU trade, concerning all the charcoal coming from countries outside the EU towards the EU. Thereafter, charcoal import from intra-EU is explored, referring to all transactions taking place within the EU. Finally, the EU's charcoal import from Nigeria is mapped.

All mass quantities are converted to tonnes and the monetary values are converted to Euros [€]. In the three trade databases, the import in monetary values include the transportation and insurance costs; therefore, are given as cost, insurance, freight [CIF]. This is different from the export values, since these exclude these services and are presented as free on board [FOB]. Within this research there is looked at the EU's charcoal import, therefore the monetary values are given as CIF.[15]

Since the three databases have slightly different values for the same charcoal trade flows, the data is aggregated to approximate the EU's charcoal import as well as possible. The total EU's import from the world is approximated by taking the average of the FAO and ITC database. The EC database is the only database from which the EU's import from extra-EU trade can be derived. The EU's import from intra-EU charcoal trade then, can be calculated by subtracting the EC database import, which represents extra-EU trade, from the FAO and ITC average. Finally, the average of the EC and ITC database is taken to approximate the EU's charcoal import from Nigeria.

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[15] Mirror data invert the reporting standards by valuing exports in CIF terms and imports in FOB terms.

After the EU's charcoal import in quantity and monetary value is derived, the average import prices per quantity can be determined, this is the market price paid by the EU. This is done by dividing the import value as CIF by the import quantity resulting in the EU's import prices [€/tonne]. The EU's import prices are calculated for global charcoal, extra-EU charcoal, intra-EU charcoal and Nigerian charcoal.

4.3 Life cycle assessment

As explained in the "Theoretical background", an LCA consists of multiple steps: the goal and scope definition, inventory analysis and impact assessment. In this section, these steps are operationalised for the two cases studied, *Scenario NG* and *Scenario EU*, in order to compare them with each other.

4.3.1 Goal and scope definition

Two charcoal products from different origins are compared. The goal of this comparative attributional single-impact LCA is to quantify the GHG emissions for the two scenarios and to find the difference between them. Additionally, within each scenario the stages most contributing to climate change, so-called hotspots, are identified.

The function of charcoal is to provide energy (i.e. heat). When using charcoal as end product the amount of energy provided is more relevant to know than the mass of the charcoal, as charcoal with the same mass can provide different amounts of energy. Therefore, the functional unit is chosen to be 1 megajoule [MJ] of charcoal combusted in the end-use stage.

Within this research, the system boundaries are defined as shown in Figure 12, consisting of the charcoal supply chain stages. This means that waste management is not considered in this research. From Johnson (2009) it is "assumed that cooled ash from the charcoal and the charcoal bag are disposed to municipal solid waste." These GHG emissions are negligible.

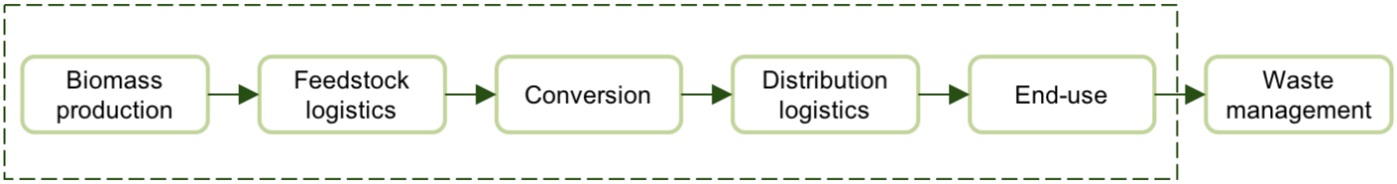

Figure 12. System boundaries for the LCA.

The studied impact category within this research is the GWP, which is defined as the total contribution to climate change by GHG emissions (Blok & Nieuwlaar, 2017). Within this research, the following direct GHG emissions are considered: CO_2, CH_4 and N_2O (Ben-Iwo et al., 2016).

These are not the only GHG emissions contributing to climate change, but they are the most commonly examined in research (Olivier et al., 2017).

The data input for the LCA is conducted using secondary literature. First, peer reviewed articles are collected by means of bibliographic databases like Scopus and Google scholar. In addition, SimaPro, an LCA software package, is used for a minor part of the specific data collection. This research does not consider site specific data, but aims to describe a country average for *Scenario NG* and considers state-of-the-art production for *Scenario EU*. Sometimes the required data was hard to find and during discussions with experts it became apparent that it was necessary to make use of relevant grey literature, such as reports from companies and newspaper articles.

4.3.2 Inventory analysis

The inventory analysis of an LCA consists of the following steps: construction of the flow model, data collection and alignment with the functional unit.

For both scenarios, a flowchart is constructed based on the *"Case study"* chapter. Figure 13 illustrates the flowcharts for *Scenario NG* and *Scenario EU*.

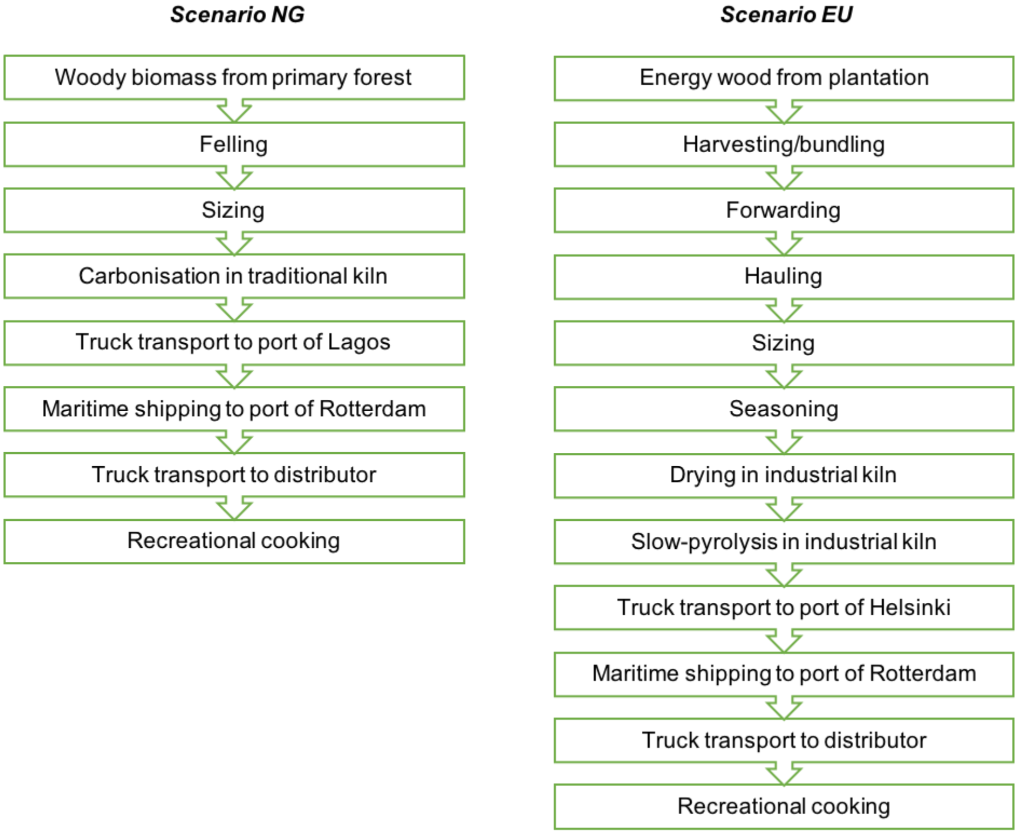

Figure 13. Flowcharts for *Scenario NG* and *Scenario EU*.

Then, for both scenarios, for every step of the flowchart data is collected. The collected data consists of the associated GHG emissions per step. GHG emissions of a bio-based product can have two origins: biogenic and fossil. Both types of emissions are considered within the inventory and listed appropriately. However, the contribution of biogenic CO_2 emissions to the net GHG emissions depends on whether biomass is replanted after harvesting, not depleting its long-term carbon stocks (Ekeh et al., 2014). When woody biomass is harvested sustainably and the combustion of biomass occurs under ideal conditions, the CO_2 emissions sequestrated are equal to the biogenic CO_2 emissions released, therefore, they do not contribute to net-CO_2 emissions. This concept is called carbon neutrality of biomass combustion (Ekeh et al., 2014). In contrast, when biomass is harvested unsustainable the biogenic CO_2 emissions are not sequestrated, therefore, contributing to net-CO_2 emissions. In *Scenario NG*, woody biomass is harvested from primary forests without replanting and therefore biogenic CO_2 contributes to the GWP. In *Scenario EU*, the woody biomass is harvested from regulated plantations and therefore biogenic CO_2 does not contribute to the GWP (Ekeh et al., 2014).

CO_2 neutral should not be confused with zero emissions. The non-CO_2 biogenic GHG emissions, like CH_4 and N_2O, released in the charcoal supply chain stages are included regardless. In addition, emissions to the environment from fossil fuel use during the entire supply chain are accounted for. Within this research, the emissions for manufacturing machinery, equipment and the kilns are not taken into account. Upstream emissions to produce fossil fuels are also not considered.

4.3.3 Impact assessment

As mentioned before, this single-impact LCA focusses on climate change and the contribution of the GHG emissions is classified as its GWP. The conventional unit of GWP is expressed in CO_2 equivalent [CO_2-eq] (Baumann & Tillman, 2004). The contribution of a GHG depends upon their radiative efficiency as well as their lifetime, relative to CO_2, therefore, the value of the GWP changes when different timeframes are considered. The United Nations Intergovernmental Panel on Climate Change [IPCC] calculated the GWPs for GHG emissions for different time intervals (Myhre et al., 2013). Within this research, the IPCC factors from 2013 are used to calculate the GWP for a 100-year period expressed in gram CO_2-eq, see Table 5.

Table 5. Global warming potential values for CO_2, CH_4 and N_2O.

Parameter	Abbreviation	Value 100 years	 20 years
Carbon dioxide	CO_2	1	1
Methane	CH_4	28	84
Nitrous oxide	N_2O	265	264

Formula 1 shows how the total GWP for each scenario is calculated, resulting in gram CO_2-eq per MJ charcoal combusted in the end-use stage.

$$\boldsymbol{Total\ GWP = GWP_{CO_2} * E_{CO_2} + GWP_{CH_4} * E_{CH_4} + GWP_{N_2O} * E_{N_2O}} \qquad [1]$$

Where:

GWP = global warming potential (characterisation factor) of specific greenhouse gas substance

E = associated emissions of specific greenhouse gas substance

The collected data from the inventory analysis and its alignment with the functional unit, using the mass balances, are given in Table 6 and Table 7.

Table 6. Mass balance and its related GHG emissions for the charcoal supply chain of *Scenario NG*.

Parameter	Unit	Oven dry *Unit*	GHG emissions *g CO2-eq/Unit*	Notes
Felling	kg wood	0.50	1.87	Table 23
Sizing	kg wood	0.50	1.87	Table 23
Carbonisation	kg wood	0.50	-	
	kg charcoal	0.04	$3.71*10^3$	Table 24
Truck Nigeria	kg charcoal	0.04	58.2	Table 25
Container ship	kg charcoal	0.04	149	Table 25
Truck Netherlands	kg charcoal	0.03	7.16	Table 25
End use	kg charcoal	0.03	-	Table 26
	MJ charcoal	1.00	118	

The mass balance is constructed starting with 1 MJ charcoal combusted in the end-use stage and working its way up. A LHV for charcoal of 30 MJ/kg is assumed (Abasiryu et al., 2016). According to FAO (2017), there is 12.5% charcoal losses in the form of dust during its distribution. The 12.5% loss is not assumed per stage, but the loss is first treated as one distribution phase, and afterwards divided among them. Continuing a 10% loss in the form of charcoal dust is assumed, occurring at the production site (Van Dam, 2017). For the traditional kiln an efficiency of 8% is considered, since green wood with a moisture content of 50% wet basis enters the traditional kiln (Openshaw, 1983).

Table 7. Mass balance and its related GHG emissions for the charcoal supply chain of *Scenario EU*.

Parameter	Unit	Oven dry *Unit*	GHG emissions *g CO2-eq/Unit*	Notes
Harvesting/bundling	kg energy wood	0.15	28.5	Table 27
Forwarding	kg energy wood	0.15	2.71	Table 27
Hauling	kg wood bundle	0.14	23.5	Table 27
Sizing	kg wood bundle	0.14	1.09	Table 27
Seasoning	kg wood	0.14	-	
Drying	kg wood	0.13	-	
Slow pyrolysis	kg wood	0.13	-	
	kg charcoal	0.04	90.3	Table 28
Truck Finland	kg charcoal	0.04	14.3	Table 29
Container ship	kg charcoal	0.04	45.0	Table 29
Truck Netherlands	kg charcoal	0.03	7.16	Table 29
End use	kg charcoal	0.03	-	
	MJ charcoal	1.00	17.1	Table 30

The mass balance is constructed starting with 1 MJ charcoal combusted in the end-use stage and working its way up. A LHV for charcoal of 30 MJ/kg is assumed (Abasiryu et al., 2016). According to FAO (2017) there is 12.5% charcoal losses in the form of dust during its distribution. The 12.5% loss is not assumed per stage, but the loss is first treated as one distribution phase, and afterwards divided among them. Continuing a 10% loss in the form of charcoal dust is assumed, occurring at the production site (Van Dam, 2017). A wood-to-charcoal conversion rate of 33% is assumed from Reumerman and Frederiks (2002). Continuing, a 2% dry matter loss for drying is considered (Whittaker et al., 2011). For seasoning a dry matter loss of 5% has been taken into account (Giuntoli et al., 2017). Also, a 2% dry matter loss occurred during sizing, as well as during the intermediate transportation and forwarding of wood energy (Whittaker et al., 2011).

4.4 Economic analysis

This section discusses the methodology of the EA. First, some important preparation steps are carried out. Then, in the technology characterisation, the technical performances together with its costs are mapped for both scenarios. Afterwards, a cost-benefit analysis is conducted, using the data collected in the technology characterisation to determine the relative economic attractiveness for both scenarios, expressed in the NPV.

4.4.1 Preparation

As discussed in the “Theoretical background”, the preparation of an EA includes: defining the aim of the analysis, its functionality, the reference technology and setting the system boundaries. The preparation step is very similar to the goal and scope definition of an LCA. The aim of this analysis is to map the cost structure for charcoal production in Nigeria and the EU.

The functionality for the EA is defined in a similar way as the functional unit in the LCA, to improve the comparability between both analyses. Therefore, the functionality defined in this research is first given in tonne charcoal and eventually given in GJ charcoal.

This study compares the two scenarios as described in the "Case study". More specifically, it compares traditional kiln production in Nigeria with industrial kiln production in the EU. The industrial technology is chosen as the reference technology, as this is the most modern commercial technology available.

The technology identification for this research only considers slow-pyrolysis as this yields the highest amount of charcoal. There are several other production methods for charcoal, such as fast-pyrolysis and flash pyrolysis, but these are not considered since these methods produce charcoal as a by-product. Also, only woody biomass is considered as feedstock input.

Finally, the system boundaries for the EA only consider the conversion and distribution logistics stage of the charcoal supply chain (Figure 14).

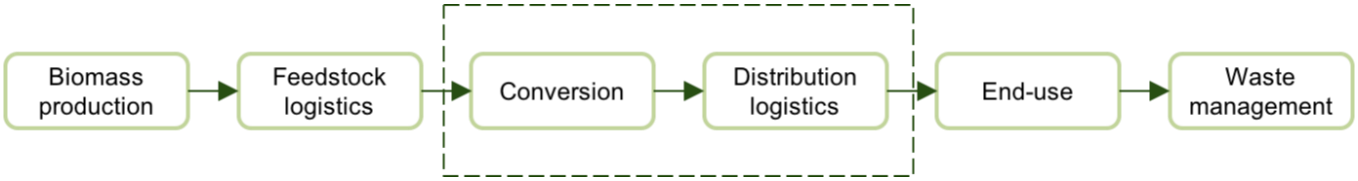

Figure 14. System boundaries for the EA.

Like the LCA, a contemporary timeframe is applied to analyse the EA. For as much as possible, the input data for the EA is country-specific. The accuracy of this analysis relies heavily on available data. Since little known research has covered this topic previously, this data is difficult to acquire. Moreover, data about prices is highly time- and location-specific, so multiple sources are consulted to improve accuracy. In addition, data was also gathered from informal sources such as online forums.

4.4.2 Technology characterisation

As already mentioned in the "Theoretical background", there are two important technology characteristics to consider: technical performance and costs.

Since the collected data comes from different sources, countries, and timeframes, this data is converted to €$_{2017}$. First, all foreign currencies are converted to 2017 values as depicted in Equation 2, using the yearly inflation rates (Table 31, Appendix D). Then, the monetary values are converted to the corresponding Euro value utilizing the following exchange rates: 1 United States Dollar equals 0.85 Euro and 1 Naira equals 0.0024 Euro.

$$\boldsymbol{P_{2017}} = \boldsymbol{P_{base\ year}} \prod_{n=base\ year}^{2016} (\boldsymbol{1} + \boldsymbol{i_n}) \qquad [2]$$

Where:

P$_{2017}$ = Total inflated costs in year 2017

P$_{\text{base year}}$ = Costs in the base year

i = inflation rate of year n

n = the year

Written out, Equation 3 looks as follows:

$$\boldsymbol{P_{2017}} = \boldsymbol{P_{base\ year}} * \left(\boldsymbol{1} + \boldsymbol{i_{base\ year}}\right) * \left(\boldsymbol{1} + \boldsymbol{i_{base\ year+1}}\right) * \left(\boldsymbol{1} + \boldsymbol{i_{base\ year+2}}\right)[\dots](\boldsymbol{1} + \boldsymbol{i_{2015}}) * (\boldsymbol{1} + \boldsymbol{i_{2016}}) \qquad [3]$$

As identified in the "Case study", the technology applied in *Scenario NG* is a traditional kiln while for *Scenario EU* an industrial kiln is used. The industrial kiln has a much higher performance in terms of conversion efficiency compared to the traditional kiln (Stassen, 2015). However, the initial investment costs for an industrial kiln are much higher than for a traditional kiln (Stassen, 2015). Both the initial investment costs and its production costs of the two scenarios are compared. The assumed technical performance and its costs are given for both *Scenario NG* and *Scenario EU* in Table 8 and Table 9.

Table 8. Production, input/output and financial parameters for *Scenario NG.*

Parameters	Unit	Value	Notes
Production			
Number of kilns per year	kilns	5.00	[a]
Kiln capacity [m3]	m3s wood/kiln	10.20	[a]
Kiln capacity [tonnes]	tonne (dry) wood/kiln	9.14	
Specific weight wood [dry]	tonne/m3s	0.896	[b]
Moisture content wood	%, wet basis	50%	[c]
Efficiency	%	8%	[d]
Labour time per kiln	persondays/kiln	100	[a]
Input/output			
Charcoal production	tonnes/kiln	0.77	
Efficiency	tonne wood (dry)/tonne charcoal	11.81	

Actual efficiency [wt]	tonne wood (wet)/tonne charcoal	23.63	
Annual input [dry]	tonne wood (dry)/year	45.70	
Annual input [wet]	tonne wood (wet)/year	91.39	
Annual output	tonne charcoal/year	3.87	
Financial parameters			
Wood (moisture 50%) costs	€/m3s	-	[e]
Charcoal sales price	€/tonne	40.98	[f]
Project time	years	15	[a]
Investment	€	145.11	[g]
Labour costs	€/labourday	2.50	[h]
Annual labour costs	€/year	70.00	
Discount rate	%	5%	[i]

[a] Data on traditional production methods is obtained from Luoga et al. (2000). [b] The specific weight of wood is conducted from Adedeji et al. (2013). [c] (Reumerman & Frederiks, 2002). [d] For the traditional kiln an efficiency of 8% is considered, since green wood with a moisture content of 50% wet basis enters the traditional kiln (Openshaw, 1983). [e] Feedstock in Nigeria is obtained for free (Fadare, 2017). [f] The charcoal is sold by the producer for 464 Naira per 50 kg (Aiyeloja & Chima, 2011). These values are obtained in 2011 and therefore calculated to Euros 2017. [g] The investments include an axe, machete, hoe, shovel, fork and chainsaw (Luoga et al., 2000). For the chainsaw, a price of 120 € is assumed. [h] Minimum labour is assumed for the Nigerian charcoal producers (USDS, 2016). [i] Finally, a discount rate of 5% is assumed (USDS, 2016).

Table 9. Production, input/output and financial parameters for *Scenario EU.*

Parameters	Unit	Value	Notes
Production			
Number of vessels	vessels	2	[j]
Capacity of one vessel	m3s wood/vessel	3	[j]
Specific weight wood [dry]	tonne/m3s	0.640	
Moisture content wood	%, wet basis	50%	[j]
Efficiency	%, mass	33%	[j]
Production time per vessel	hours	12	[j]
Capacity factor	prod. hours/total hours	0.9	[j]
Input/output			
Efficiency	tonne wood (dry)/tonne charcoal	3.03	
Actual efficiency [wet]	tonne wood (wet)/tonne charcoal	6.06	
Capacity	tonne charcoal/year	925	
Annual input [dry]	tonne wood (dry)/year	2,523	
Annual input [wet]	tonne wood (wet)/year	5,046	
Annual output	tonne charcoal/year	833	
Financial parameters			
Wood costs	€/tonne green wood	28.06	[k]
Charcoal sales price	€/tonne	400	

Project time	years	10	[j]
Initial investment	€	617,127	[j]
O&M costs	percentage of investment	10%	[j]
Discount rate	%	9.5%	[l]

[j] For the industrial kiln, the production parameters and the financial parameters are obtained from Reumerman & Frederiks (2002). [k] For Scenario EU a feedstock price of 188 € for 6.7 tonnes of green wood according to Suopajärvi and Fabritius (2013) is assumed. [l] The discount rate is approximated to be 9.5% (Competition & Markets Authority, 2015).

4.4.3 Cost-benefit analysis

The cost-benefit analysis provides insights on associated costs and benefits for each scenario. It does this by calculating the NPV. The NPV takes all costs and benefits associated per production technology and discounts them with a yearly discount rate. Using the converted values, the NPV for charcoal production in both scenarios is calculated using Equation 4.

$$\boldsymbol{NPV} = \sum_{i}^{n} \frac{\boldsymbol{B_i - C_i}}{\boldsymbol{(1 + r)^i}} \qquad [4]$$

Where:

NPV = net present value of the project at the beginning of the first year (t = 0)

B_i = benefits of the project in year i

C_i = costs of the project in year i (including the initial investments at the beginning of the project, t = 0)

r = discount rate

n = life time of the project

With the discount rate, it becomes possible to convert all future costs and benefits to their present value. Companies normally set their discount rate equal to their weighted average costs of capital [WACC], this is done so that a project at least yields benefits above the cost of lending the capital they need to invest into a project. For *Scenario NG*, this study assumes a 5% discount rate, as this is the maximum interest rate for Nigerian agricultural loans (Premium Times Nigeria, 2016). For *Scenario EU*, the WACC in the energy sector lies around 9.5% (Competition & Markets Authority, 2015).

4.5 Combined sensitivity and uncertainty analysis

Moreover, the results chapter also conducts a combined sensitivity and uncertainty analysis of the underlying assumptions for both the LCA and EA, in order to increase the reliability of this research and to explain the robustness of the results.

It is important to know the difference between a sensitivity analysis and uncertainty analysis. A sensitivity analysis determines how sensitive the results are to assumptions made in the methodology, by changing these assumptions (Eriksson, 2007). Assumptions made in the methodology are varied and the results are compared to the initial results (referred to as the base case). This provides insight on the difference in the results when making incorrect assumptions in the methodology. An uncertainty analysis is executed in order to determine how uncertain an output is, by acknowledging how uncertain the input data is and how this uncertainty in the end affects the results (Eriksson, 2007). The uncertainty analysis is based on the data input uncertainty. Where in the base case the average or default value is considered, in the uncertainty analysis a range between the minimum and maximum values is considered.

For the LCA, first, the GWP for a 100-year period is changed into the GWP for a 20-year period. Secondly, the effect of sustainable and unsustainable forestry is investigated, specifically the results it has on the conversion and end-use stage. In case of sustainable forestry, the biogenic CO_2 released is sequestrated by newly planted trees, therefore considered as carbon neutral. With unsustainable forestry, the released biogenic CO_2 emissions are not sequestrated and these emissions contribute to the net-CO_2 emissions and to the total GWP.

Afterwards for both scenarios a combined sensitivity and uncertainty analysis is performed for the LCA. For *Scenario NG*, varieties in feedstock logistics are considered, because of their negligible contribution to the total GWP. The use of a masonry mound kiln has been included to account for sensitivity of its emissions released during the conversion stage, by changing the kiln type. The sensitivity of transportation by truck and ship is accounted for by varying the type of vehicle used for transport, specifically considering different sizes. Also, the uncertainty of the range of charcoal combustion emissions in the end-use stage is examined. Finally, the uncertainty in data due to the LHV of charcoal is examined. The LHV depends on a lot of factors, such as the wood type used and moisture content of the wood. The LHV is important to consider, because changing the LHV affects all stages in the supply chain, as the mass of charcoal needed in the end-stage to combust 1 MJ of charcoal depends on its LHV.

A similar combined analysis is applied to *Scenario EU*. This analysis considers the sensitivity in transportation, including different types of trucks and containerships. Furthermore, the uncertainty of the emissions due to charcoal combustion in the end-use stage is considered. Finally, the uncertainty of the charcoal's LHV.

For the EA, the following variables are varied for *Scenario NG* in the combined sensitivity and uncertainty analysis, namely: the discount rate, cost of labour and feedstock price. Additionally, the investment costs are varied by including or excluding a chainsaw instead of an axe in the initial investment. *For Scenario EU*, more parameters are varied: feedstock price, discount rate, charcoal sales price, O&M costs, investment costs and the specific weight of wood (dry) are considered.

5. Results

This chapter discusses the results of each analysis separately: from the TDC the EU's charcoal import is presented. Then, from the single impact LCA, the GWP for both *Scenario NG* and *Scenario EU* are derived. Finally, the costs and benefits for charcoal produced in Nigeria and sustainable charcoal produced in the EU is determined from the EA with their respective NPVs. Both the LCA and EA are supplemented with a combined sensitivity and uncertainty analysis.

5.1 Trade database comparison

This subchapter compares the EC, ITC and FAO trade databases to map the EU's charcoal import in quantity [tonne] and monetary value [€] from the world, extra-EU, intra-EU and Nigeria. Table 10 provides a summary of the EU's import data for the year 2016, which is explained in more detail below. First, the EU's import quantity is discussed, followed by the EU's import value, finally, by dividing the monetary value of the import by the import quantity, the import price is given. Presented numbers in this section are given for the year 2016, unless otherwise stated. The original data from these three trade databases can be found in Appendix E.

Table 10. Overview of the EU's charcoal import in quantity and monetary value from the world, extra-EU, intra-EU and Nigeria, together with the EU's charcoal import prices for these regions in 2016.

From	**Quantity** *tonne*	**Monetary value** *€*	**Import price** *€/tonne*
World	978,329	405,735,380	415
Extra-EU	657,870	235,922,720	359
Intra-EU	320,459	169,812,660	530
Nigeria	146,730	33,583,889	229

5.1.1 European Union's import quantity

Figure 15 illustrates the EU's charcoal import in quantity from the world, extra-EU, intra-EU and Nigeria. It becomes apparent that the EU's charcoal import from these regions have all increased over the period 2003 through 2016.

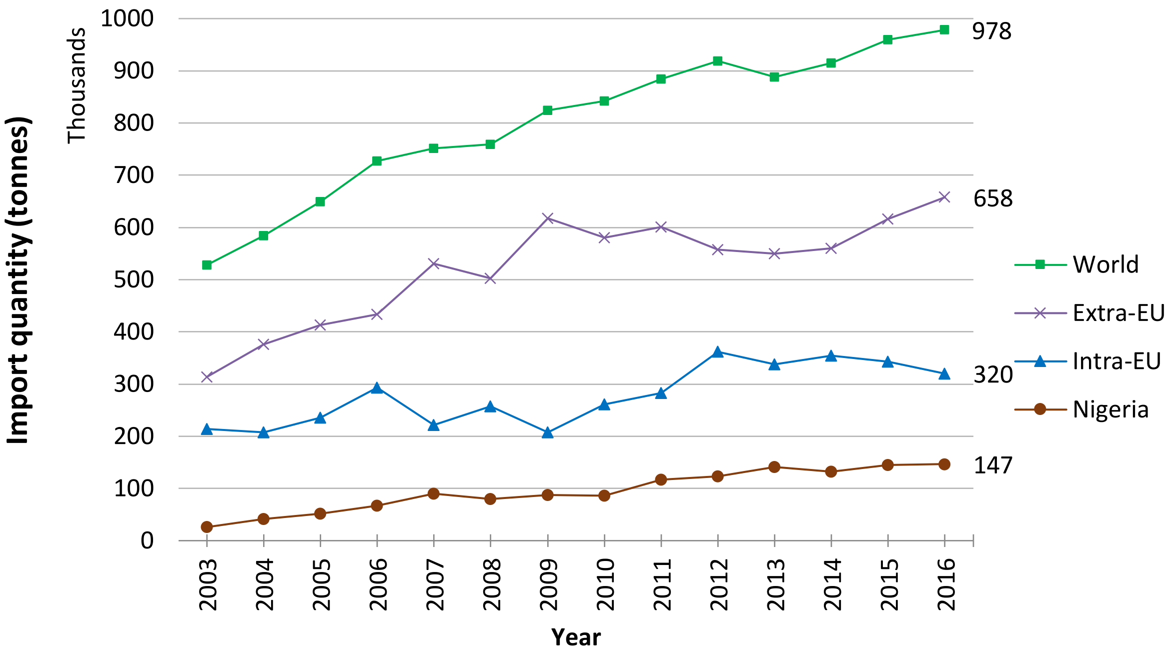

Figure 15. EU's import in quantity from the world, extra-EU, intra-EU and Nigeria over the period 2003 – 2016.

The graph above shows that an average of 978 ktonnes of global charcoal is imported by the EU from the world. This is nearly one third of the charcoal that is imported worldwide. A total of about 658 ktonnes was imported by the EU from extra-EU trade. This imported charcoal quantity originated from 60 countries outside the EU. The five largest extra-EU suppliers in quantity besides Nigeria are: Ukraine, Cuba, Paraguay, Namibia, Indonesia (EC, 2017). This implies that more than 320 ktonnes of the EU's charcoal import quantity is traded between the EU Member States, referred to as intra-EU trade.

This paragraph zooms in on the EU's import of Nigerian charcoal. Nigeria was the biggest charcoal supplier of the EU, accounting for 147 ktonnes or 22% of the extra-EU trade (Table 10). As illustrated in Figure 15, from 2003 through 2016, the import from Nigeria increased with 466%. Reported by both ITC (2017) and EC (2017), Poland, Belgium, Germany, Portugal and the United Kingdom were the largest importers of Nigerian charcoal within the EU. According to the mirror data[16] of the ITC database, Nigeria exported a total of 196 ktonnes of charcoal, 82% of this total Nigerian export went to the EU. However, this mirror data is inconsistent with the direct data from the ITC database on Nigerian charcoal exports. Nigeria reports an average export of around 40 ktonnes per year to the world, with an outlier in 2009 where the export amounted to almost 680

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[16] In this case, the mirror data is reported by the importing countries, thus the EU, how much charcoal they import.

ktonnes. Both figures are presented in the Appendix E. An explanation for the inconsistent data could be illegal trade that is not reported by Nigeria. This confirms again the uncertainty of the numbers from the trade databases and that the results from this trade database comparison must be dealt with carefully.

5.1.2 European Union's import value

The import values include insurance and transportation costs, therefore are given as CIF values. The EU's charcoal import in monetary value, as illustrated in Figure 16, shows a similar trend as the charcoal import in quantity. Since 2003, the EU's charcoal import has steadily increased through 2016. The EU imported for almost 406 M€ of global charcoal. Note that the intra-EU trade shows a relatively steeper increase in monetary value compared to the import in quantity between 2003 and 2016: the monetary value increased with 129%, while the quantity increased with 49%. Between 2003 and 2016, the increase of the total monetary value of Nigerian charcoal imports is similar to the quantity import: the monetary value increased with 469% and the quantity increased with 466%. The EU's charcoal import value from extra-EU trade was 236 M€ and import from Nigeria accounted for 14% of this value. Even though the EU's charcoal import from Nigeria was largest in terms of quantity, this is not the case for the charcoal in import value from Nigeria.

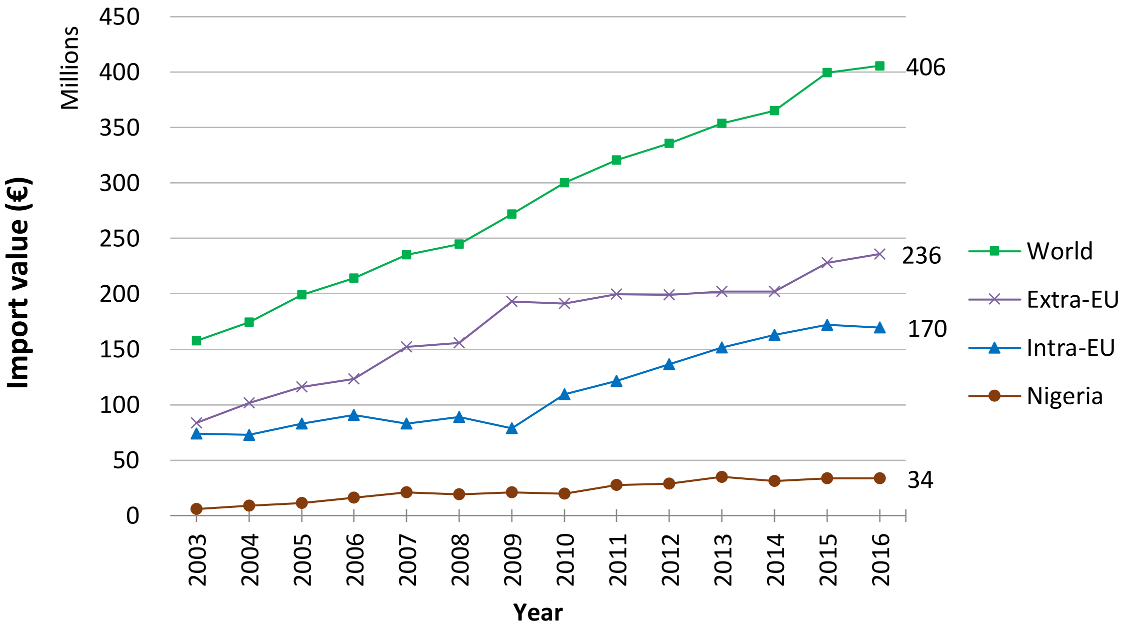

Figure 16. EU's import value from the world, extra-EU, intra-EU and Nigeria over the period 2003 – 2016.

5.1.3 European Union's import prices

By dividing the import value by the import quantity, derived from the TDC, the EU's import prices for global charcoal, extra-EU charcoal, intra-EU charcoal and Nigerian charcoal are approximated. These import prices include the monetary values as CIF, and therefore are given in CIF import price. An overview of the import prices for 2016 are presented in Figure 17, this is explained in more detail below. As the graph below shows, there is a large difference between the EU's import prices for charcoal from these regions.

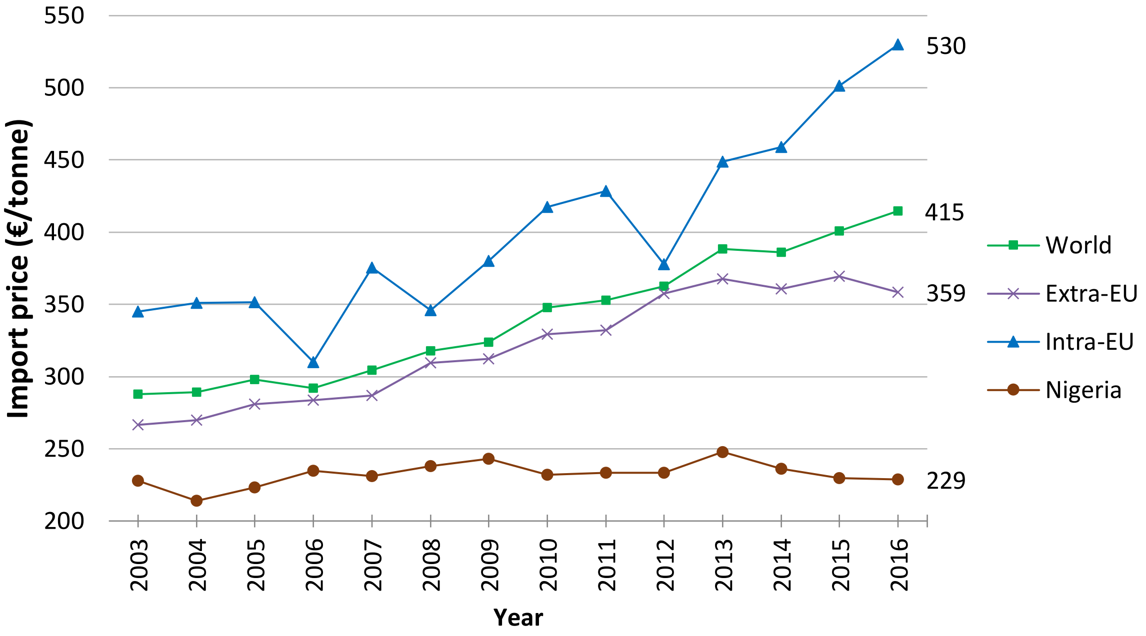

Figure 17. EU's import prices for global, extra-EU, intra-EU and Nigerian charcoal over the period 2003 – 2016.

For the EU, the intra-EU import price is highest (530 €/tonne), followed by the import price for charcoal from the world (415 €/tonne). The EU's import price for Nigerian charcoal, is less than half of the intra-EU import price, namely 229 €/tonne. The EU's import price for Nigerian charcoal is 130 €/tonne lower than the import price for extra-EU charcoal. As a final remark, the EU's import price for Nigerian charcoal is one of the lowest prices worldwide, even compared to the other five biggest extra-EU charcoal suppliers of the EU (Figure 18).

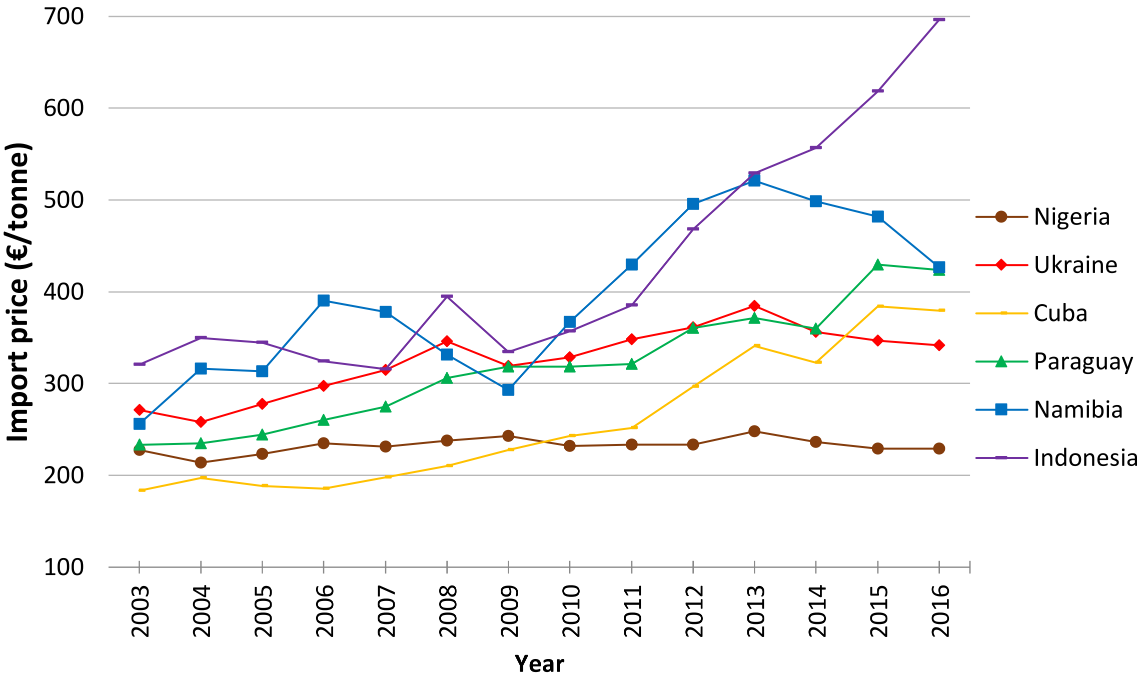

Figure 18. EU's import prices for charcoal presented for the top 6 extra-EU suppliers, according to the EC database.

5.2 Global warming potential

This subchapter presents the GWP of *Scenario NG* and *Scenario EU*. Figure 19 provides a summary of the GWP per scenario, where the associated GHG emissions are summed up in CO_2-eq per MJ charcoal combusted in the end-use stage. First, the results of *Scenario NG* are elaborated on, where the EU imported charcoal produced in Nigeria. Afterwards, the results of *Scenario EU* are explained, where charcoal is sustainably produced in the EU and traded among the EU Member States.

5.2.1 Global warming potential *Scenario NG*

The GWP per MJ charcoal for *Scenario NG* is 284 g CO_2-eq. Figure 20 illustrates that the conversion stage and the end-use stage have the largest influence on the GWP. The large contribution of the conversion stage and the end-use stage is due to unsustainable forestry, namely (illegal) harvesting of woody biomass without replanting. The biogenic CO_2 released during the conversion and end-use is considered and therefore contributes to the overall GWP of *Scenario NG*. In addition, due to the traditional earth kiln method used in the conversion stage, incomplete combustion occurs, resulting in CH_4 emissions further contributing to the GWP. Felling and sizing only contribute a very low amount to the total GHG emissions; therefore, this stage is not elaborated on further. Consistent with findings by Van Dam (2017), transportation has a relatively low impact on the total amount of GHG emissions.

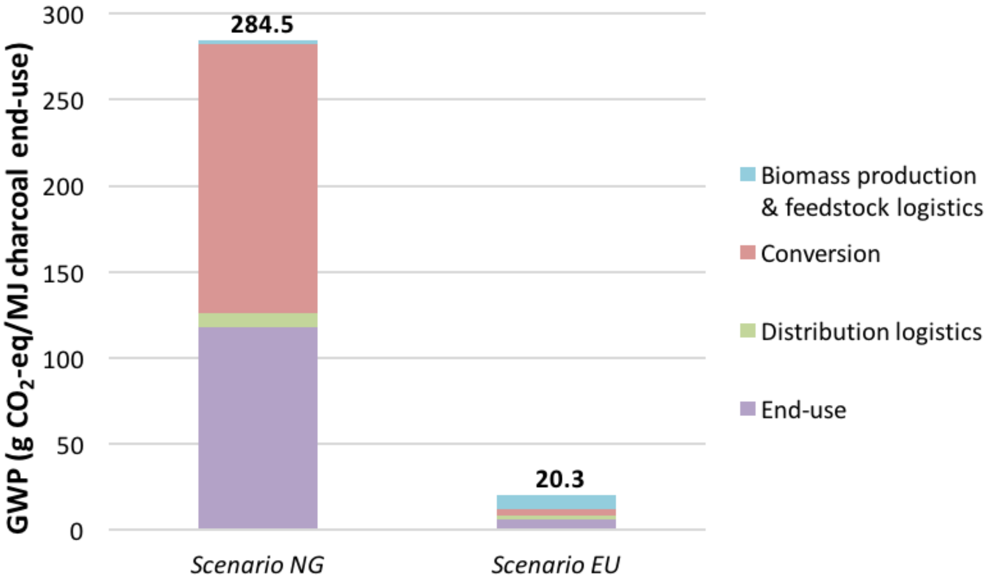

Figure 19. GWP of *Scenario NG* and *Scenario EU*.

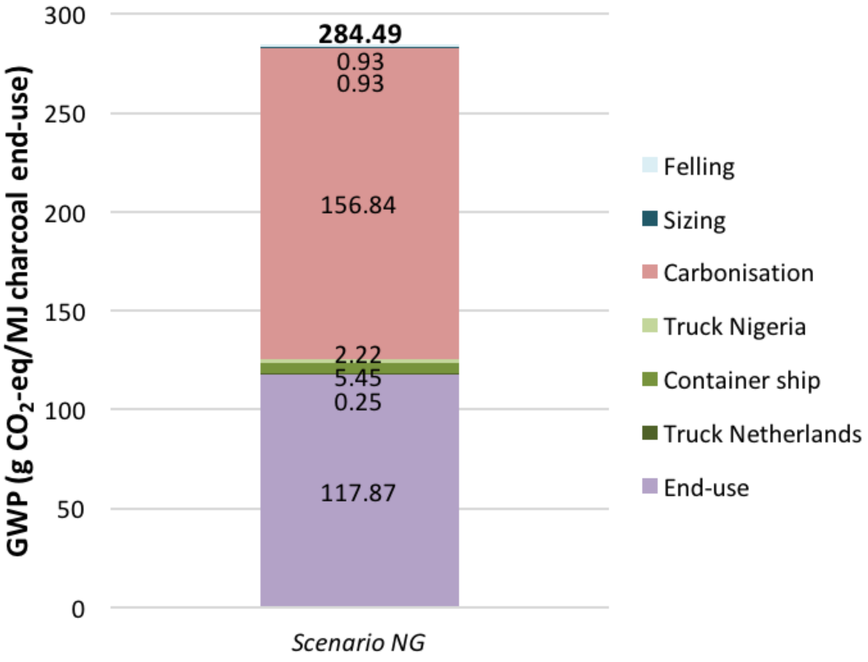

Figure 20. GWP for *Scenario NG* per MJ charcoal combusted in the end-use stage.

5.2.2 Global warming potential *Scenario EU*

The GWP for *Scenario EU* is 20 g CO_2-eq/MJ, as can be seen in Figure 21. The charcoal is considered CO_2 neutral since the woody biomass is harvested sustainably and the biogenic CO_2 released does not contribute to the total GHG emissions. What stands out is that GHG emissions in the end-use stage contributes most to the total GWP. Since due to incomplete charcoal combustion CH_4 is released, contributing to the total GWP. Secondly, harvesting/bundling account for around 4 g CO_2-eq/MJ, caused by the fossil fuels consumed in the various machinery needed. The reason for the GHG emissions in the conversion stage are caused by additional fossil fuels needed to provide the heat needed for slow-pyrolysis. Only a very small portion in the conversion stage is caused by biogenic CH_4 emissions. Finally, hauling contributes more to the GWP than the total distribution stage.

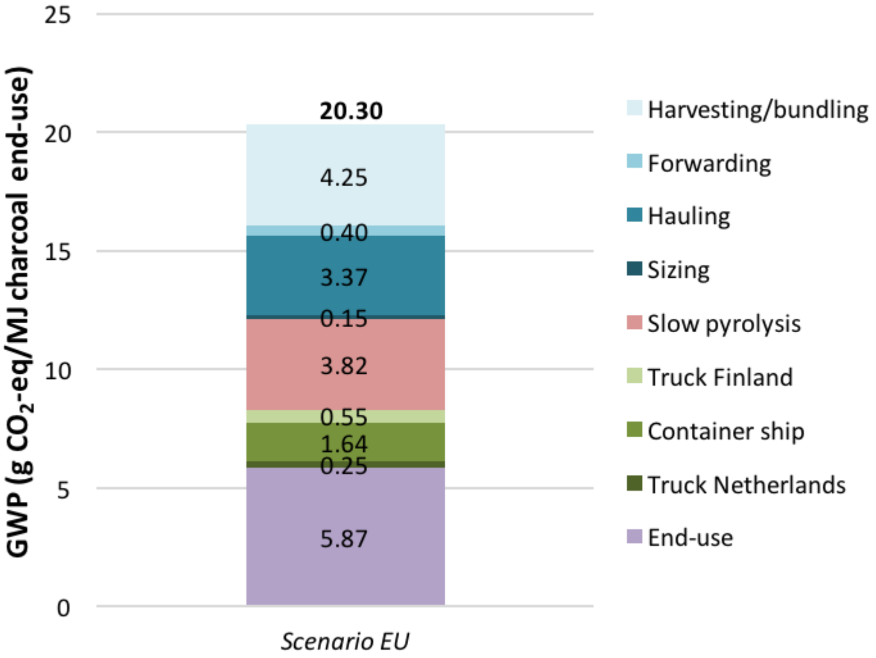

Figure 21. GWP for *Scenario EU* per MJ charcoal combusted in the end-use stage.

5.2.3 Global warming potential comparison

As Figure 19 shows, *Scenario NG* clearly has a much higher GWP, namely 284 g CO_2-eq/MJ, over 10 times more than *Scenario EU*, namely 20 g CO_2-eq/MJ. The difference in GWP between the two scenarios is 264 g CO_2-eq/MJ. This means that per MJ charcoal combusted in the end-use stage 264 g CO_2-eq can be mitigated by producing the charcoal sustainably in the EU instead of importing unsustainably produced charcoal from Nigeria. Figure 22 shows the relative distribution of the contribution per charcoal supply chain stage for both scenarios. The main differences between the scenarios are discussed in more detail below.

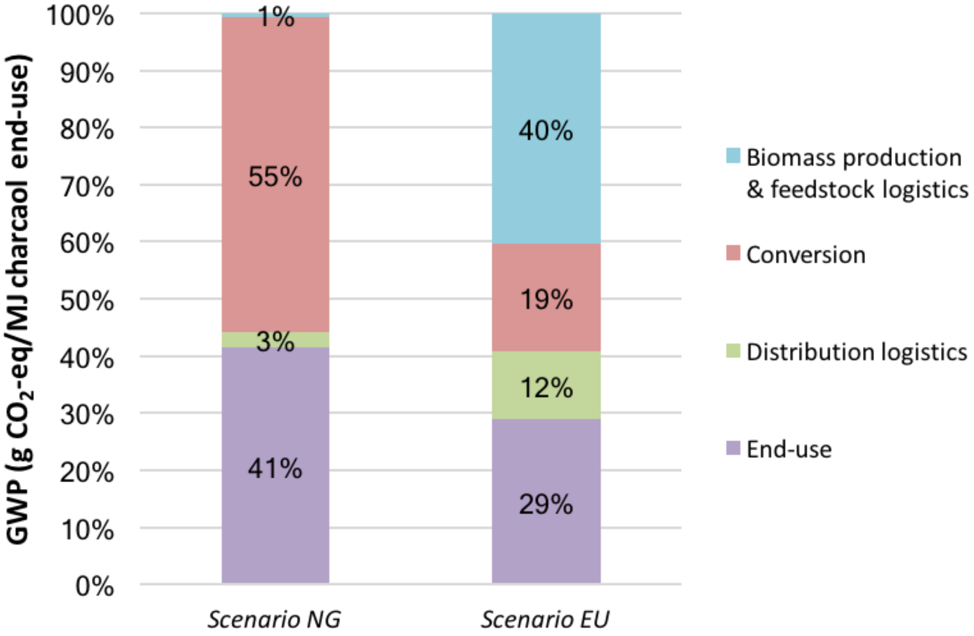

Figure 22. GWP comparison between *Scenario NG* and *Scenario EU* in a stacked column.

For *Scenario NG* biomass production is not considered, since woody biomass is acquired illegal from natural forests. The 1% from biomass production and feedstock logistics is caused by the feedstock logistics, namely the use of a chainsaw. The biomass production and feedstock logistics stage for *Scenario EU* contributes 40% to its total GWP, where forest management is included. While these stages contribute most to the GWP, sustainable forestry drastically reduces the net-CO_2 emissions in the conversion and end-use stage of *Scenario EU*, due to biogenic CO_2 released is considered as CO_2 neutral.

For *Scenario NG*, the conversion stage contributes most to its total GWP, namely 55% (157 g CO_2-eq/MJ). While in Scenario EU, the conversion stage contributes only little under 20% (4 g CO_2-eq//MJ). The conversion emissions calculated for this research are compared with a recently published study. Van Dam (2017) collected a range of emission values regarding the conversion stage.[17] The varying emissions are due to differing production methods. The minimum, average and maximum conversion emissions from this report are taken into account to compare the results of this research with literature. Figure 23 shows this range of emission values for the conversion

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[17] The aggregated values are extracted from Table 7 in “The charcoal transition: Greening the charcoal value chain to mitigate climate change and improve local livelihoods” (Van Dam, 2017).

stage, according to FAO (2017), and are applied to the mass balances of *Scenario NG* and *Scenario EU*. The conversion emissions in *Scenario NG* should be near the maximum due to the inefficient traditional kiln, while *Scenario EU* conversion emissions should be close to the minimum due to the efficiency of industrial kilns. For *Scenario NG,* the result is as expected, as the conversion emissions lie between the average and maximum, while *Scenario EU* is at the minimum. This suggests that emission values associated with the conversion stage found in this research have a high validity.

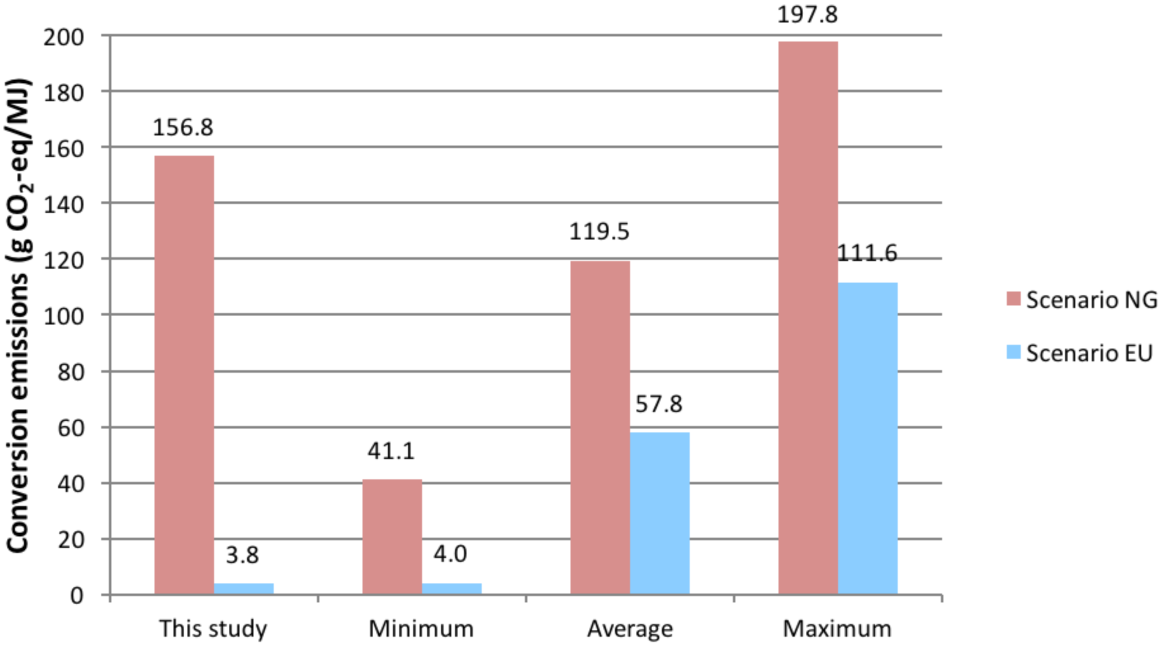

Figure 23. Conversion emissions compared to Van Dam (2017).

For *Scenario NG,* the distribution logistics stage has a total of 7.9 g CO_2-eq/MJ, while for *Scenario EU* this is somewhat lower accounting for 2.4 g CO_2-eq/MJ. However, when looking at the percentage contribution, for *Scenario NG* it is only 3% of the total GWP, while for *Scenario EU* it is 12% of the total GWP. For both scenarios, it is only a minor contributor to the total GWP.

In both scenarios, the end-use stage is an essential part of the total GWP (Figure 22). For *Scenario NG,* this is 41% or 118 g CO_2-eq/MJ and for *Scenario EU* it is 29%, specifically 6 g CO_2-eq/MJ. The large difference between these scenarios is caused by the biogenic CO_2 contributing to the total GWP of *Scenario NG*, but excluded in the GWP for *Scenario EU*. Still in both scenarios CH_4 is released due to incomplete charcoal combustion in the end-use stage. The release of CH_4 is a significant contributor to the GWP of both scenarios, therefore it should not be assumed that even if charcoal is produced sustainably, the consumption of charcoal does not emit any GHG emissions.

Finally, due to the low charcoal yield of the traditional kilns in *Scenario NG*, more wood is needed to produce the same amount of charcoal in comparison with *Scenario EU*, where industrial kilns are employed.

5.2.4 Combined sensitivity and uncertainty analysis of the life cycle assessment

First, a sensitivity analysis is executed where the time interval of the calculated GWP is changed. Then, per scenario a combined sensitivity and uncertainty analysis of the data input is included.

First, the GWP for a 100-year period is changed into the GWP for a 20-year period. Table 11 shows that both scenarios have a higher GWP for the 20-year period. Due to methane's relatively short lifetime the GWP of methane for a 20-year period is larger than over 100 years. In *Scenario NG,* this results in an increase of more than 100 g CO_2-eq of the total GWP, resulting in 392 g CO_2-eq/MJ. Methane is released during the conversion stage due to incomplete combustion of biomass in traditional kilns. Also, a small amount of emissions is added during the end-use stage due to incomplete combustion of charcoal in both scenarios. *Scenario EU* increases about 1.5 times compared to a GWP period of 100 years, resulting in 32 g CO_2-eq/MJ. This extra contribution is also due to methane released in the end-use stage due to incomplete combustion of charcoal. Looking at the influence of the GWP for a 20-year time interval, the difference in GWP between the scenarios has become even bigger.

Table 11. GWP *Scenario NG* and *Scenario EU* for a 100-year and 20-year time interval.

Parameter	Unit	*Scenario NG*	*Scenario EU*	Difference
GWP 100	$g\ CO_2\text{-}eq/MJ$	284.49	20.30	264.19
GWP 20	$g\ CO_2\text{-}eq/MJ$	392.37	31.91	360.46

Additionally, the influence of sustainable and unsustainable forestry is considered. In this sensitivity scenario, the effect of sustainable forestry is assessed by considering the woody biomass of *Scenario NG* to be sustainable and the woody biomass of *Scenario EU* to be unsustainable. It serves to illustrate the effect that the type of forestry, either unsustainable or sustainable, has on the conversion and end-use stage, see Table 12. This analysis does not change the type of production kiln used, and also does not consider the effect that sustainable/unsustainable forestry has on other stages. As becomes apparent, when sustainable forestry is considered in Nigeria and unsustainable forestry is considered in the EU, the conversion and end-use stage are higher for the EU. Therefore, it should not readily be assumed that charcoal produced in the EU is always a more sustainable choice than Nigerian charcoal. In the end, this sensitivity scenario shows that sustainable charcoal produced in Nigeria will be a better choice than unsustainable charcoal from the EU.

Table 12. Influence of sustainable and unsustainable forestry on *Scenario NG* and *Scenario EU*.

Parameter	Unit	*Scenario NG*		*Scenario EU*	
		Conversion	**End-use**	**Conversion**	**End-use**
Sustainable forestry	*g CO_2-eq/MJ*	50.59	5.87	3.82	5.87
Unsustainable forestry	*g CO_2-eq/MJ*	156.84	117.87	55.64	117.87

Next, Figure 24 presents a combined sensitivity and uncertainty analysis of *Scenario NG* which is explained first. Afterwards, in Figure 25, this same combined analysis for *Scenario EU* is illustrated and explained

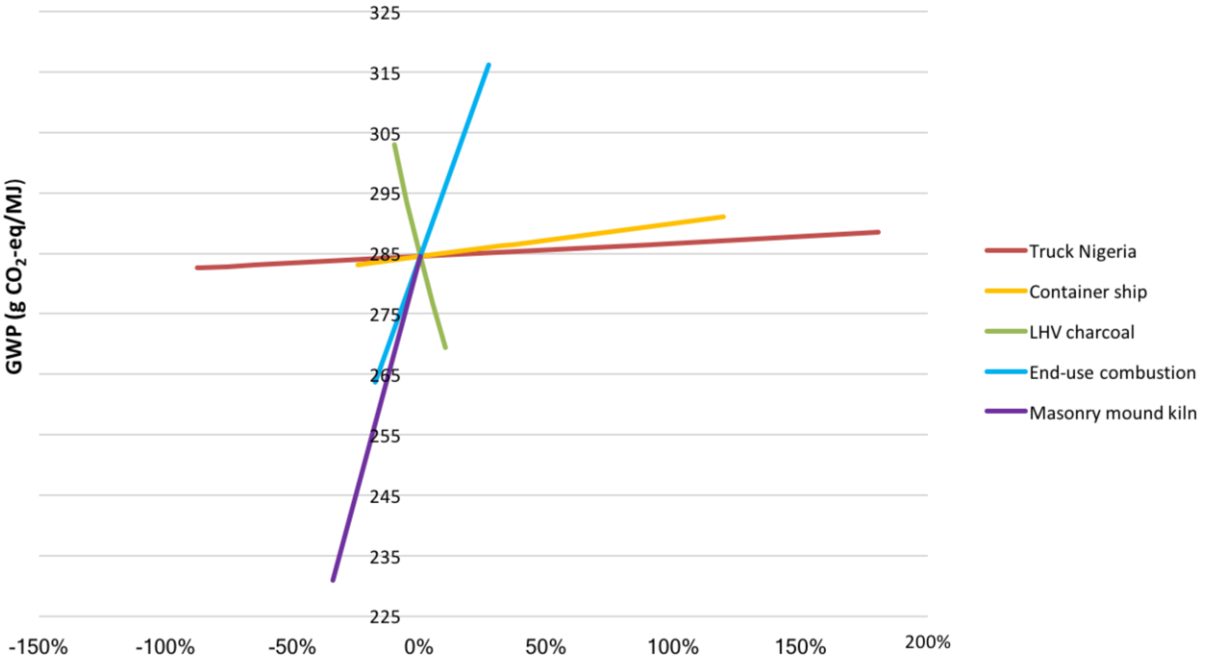

Figure 24. Combined sensitivity and uncertainty analysis for the GWP of *Scenario NG.*

The analysis of *Scenario NG* clearly shows that the outcomes of the LCA vary relatively much when changing a single data point. Changing the kiln type from a traditional mound kiln to a masonry mound kiln can decrease the GWP with 50 g CO_2-eq/MJ. The majority of this decrease is caused by the fact that the masonry mound kiln has fewer emissions during conversion. A minor part of the reduction can be attributed to less woody biomass needed for this type of kiln and therefore less emissions are emitted during the previous stages. Changing the type of truck or type of ship has a relatively low impact on the total GWP of *Scenario NG*, the difference between utilizing the smallest vehicle and the largest vehicle does not alter the GWP with more than 10 g CO_2-eq/MJ. When the uncertainty of charcoal combustion in the end-use stage is considered, considering the lower and upper emission factor of combustion, the GWP ranges between around 265 and 315 g CO_2-eq/MJ. As discussed in the "Methodology", the LHV is intertwined with the respective emissions of all stages. Varying the LHV results in a range of around 30 g CO_2-eq/MJ.

A similar combined sensitivity and uncertainty analysis for *Scenario EU* is illustrated in Figure 25. This analysis takes a different emission value up until and including the conversion phase into account, considers the sensitivity in transportation including different types of trucks and containerships, the uncertainty of the charcoal combustion emissions in the end-use stage and the uncertainty of the charcoal's LHV. Also for *Scenario EU* the effect of the type of vehicle has a relatively small influence on the outcome of the GWP. The variance in charcoal emissions during combustion in the end-use stage has the highest influence on the total GWP of *Scenario EU*. Varying the LHV value has a much smaller effect in this scenario than it has on *Scenario NG*, only affecting the total GWP with approximately 5 g CO_2-eq/MJ.

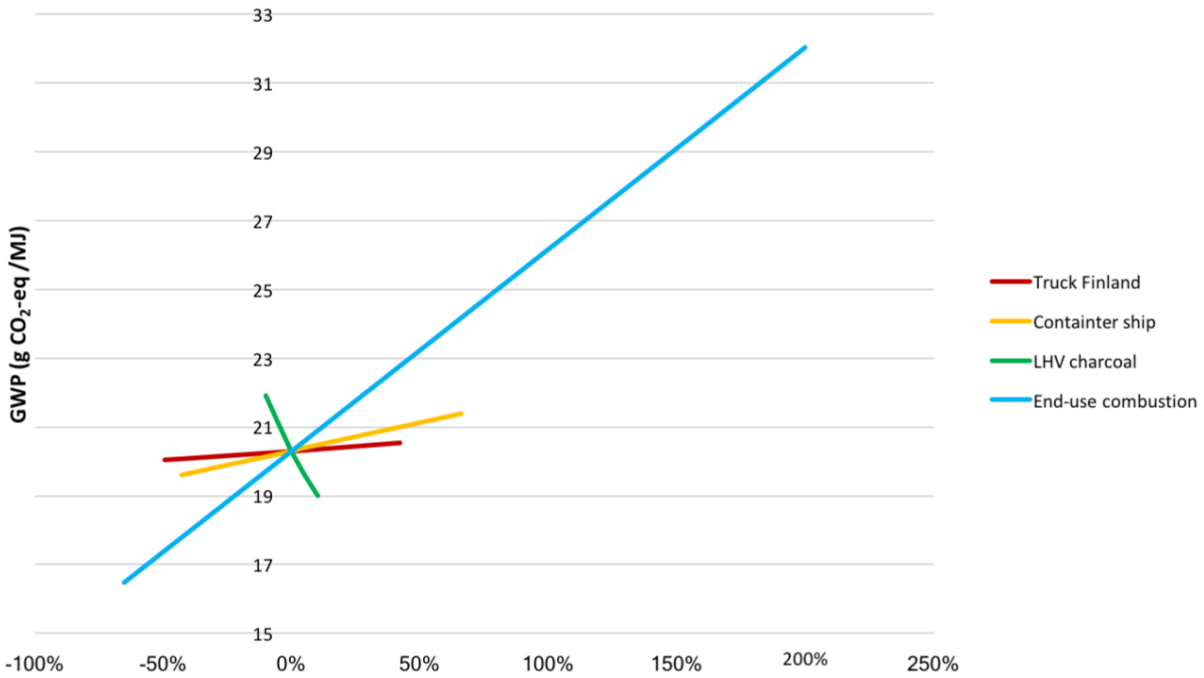

Figure 25. Combined sensitivity and uncertainty analysis for the GWP of *Scenario EU.*

To conclude, the results of *Scenario NG* are specifically sensitive to changing the type of production method, i.e. switching to a masonry mound kiln. For *Scenario EU*, varying the emissions of charcoal combustion in the end-use stage has the largest impact on the results. Varying the combustion emissions also has a significant effect on the GWP of *Scenario NG*.

As can been seen in this combined sensitivity and uncertainty analysis, the results are sensitive to the underlying assumptions, however, all cases considered, unsustainable charcoal from Nigeria has a higher GWP than sustainable charcoal produced in the EU.

5.3 Cost-benefit analysis

A cost-benefit analysis for both scenarios is conducted. First, the resulting NPV for *Scenario NG*, charcoal production in Nigeria, is discussed. Afterwards, the NPV for *Scenario EU*, sustainably produced charcoal in the EU, is elaborated upon. This is supplemented with a combined sensitivity and uncertainty analysis of the calculated NPV.

5.3.1 Cost-benefit analysis *Scenario NG*

In this section, the NPV is calculated for *Scenario NG*. Table 13 shows how the costs of Nigerian charcoal are accumulated according to literature. For a more detailed explanation, see Appendix F.

Table 13. Accumulated cost structure of Nigerian charcoal according to literature.

Parameter	Unit	*Scenario NG*	Notes
Feedstock price	*€/tonne wood*	-	Fadare, 2017
Production costs	*€/tonne charcoal*	21	Aiyeloja & Chima, 2011
Producer price	*€/tonne charcoal*	41	Aiyeloja & Chima, 2011
Retail price	*€/tonne charcoal*	104	Novus Agro, 2016
Export price [FOB]	*€/tonne charcoal*	181	Daramola & Ayeni, 2016

For *Scenario NG*, initially it was assumed that the labour costs are 2.50 €/labour-day (Nigerian minimum wage), the initial investment costs are around 25 €, feedstock is obtained for free and the charcoal sales price of the producer is approximately 41 €/tonne. It becomes apparent that the benefits do not exceed the costs, resulting in a negative NPV (Table 14), with associated production costs of over 326 €/tonne. In other words, it is not economically viable to produce charcoal in Nigeria under these assumptions.

Luoga et al. (2000) published a paper in which they stated five reasons for the charcoal production in eastern Tanzania to be profitable. The first reason is the very low capital investment. The second reason is free labour: Luoga et al. (2000) suggest that farmers and their families (i.e.

households) work for no wage due to a lack of alternative sources of income. The third reason is that feedstock is acquired for free, the trees are cut illegally and without payment to a third party. This claim is in accordance with Vos and Vis (2010): "[…] the cost of the resource itself (wood) is rarely factored into the final price" (p. 40). Fourth, locals have a lack of concern of externalities associated with charcoal production such as deforestation and air-pollution. Lastly, the high demand for charcoal is named as a reason for the local population to produce charcoal with traditional kilns. The first, third, fourth and fifth reasons mentioned in the article are in line with charcoal production in Nigeria, as explained in the "Case study". Contrary to the second reason, this research assumed the legal minimum wage of Nigeria, however, this cost-benefit analysis of *Scenario NG* suggests that in Nigeria, like Tanzania, labour costs are far below minimum wage, otherwise charcoal production is simply not economically viable.

Therefore, the initial assumption of the labour costs is reduced to 0.14 €/labour-day, then the production costs become a little over 21 €, resulting in a positive NPV of 684 € with a project runtime of 15 years. Profit from charcoal production in Nigeria can only be realised with low capital investments, assuming almost unpaid labour and when the feedstock is obtained for free. It becomes apparent that the charcoal produced in Nigeria is sold at a price below its true value. Therefore, charcoal producers are forced to employ 'free labour' and acquire feedstocks illegally. This is acknowledged by Vos and Vis (2010), mentioning that sustainable efforts will likely continue to be undermined, since the illegal and informal production of charcoal will avoid labour and feedstock costs. In case of illegally logged wood for charcoal production and the price of the feedstock input is economically neglected, charcoal prices do not reflect their real value (Sander et al., 2011). Therefore, it is also extremely difficult to adopt sustainable alternatives such as (semi-)industrial kilns or wood plantations, since the higher investment prices are not rewarded (Sander et al., 2011).

5.3.2 Cost-benefit analysis *Scenario EU*

Previous research on charcoal production costs of industrial kilns indicates that costs are dependent of specific production method as well as the feedstock used as input (Garcia-Nunez et al., 2017). The Lurgi process, for example, is a large-scale charcoal production technology that is employed in Australia, with production costs around 320 €/tonne charcoal. While another technology called Lambiotte has associated production costs of 360 €/tonne charcoal. Furthermore, for the twin-retort system 380 €/tonne charcoal was found as production costs. In the EU, the most common production technologies used are the Lambiotte and Carbo Twin Retort systems (Garcia-Nunez et al., 2017). According to Suopajärvi and Fabritius (2013), in Finland, the "[…] analysis of the supply chain yields total charcoal production costs of 268 to 478 €/t charcoal from logging residues" (p. 1200), averaging around 373 €/tonne, which is in accordance with Garcia-Nunez et al. (2017).

In *Scenario EU,* operation and maintenance costs are assumed to be 10% of investment costs (Reumerman & Frederiks, 2002). The prices mentioned in this section assume a feedstock price of 188 € for 6.7 tonnes of green wood, in accordance with Suopajärvi and Fabritius (2013). The discount rate is assumed to be 9.5% as explained in the "Methodology" and the NPV is calculated for a project time of 10 years. Under these assumptions, the NPV is 197,390 €, with the production costs of 318 €/tonne charcoal. Despite the relatively high initial investment costs for the kiln, it is economically viable to produce charcoal in the EU, under the assumption that the charcoal is sold for 400 €/tonne by the producer.

Moreover, as stated earlier, the efficiency of industrial kilns is much higher than traditional kilns. In *Scenario EU*, using an industrial kiln, only 3.03 tonnes of dry wood are needed to produce 1 tonne of charcoal compared to the around 11.81 tonnes of dry wood needed for traditional kilns in *Scenario NG*.

5.3.3 Combined sensitivity and uncertainty analysis of the economic analysis

This combined sensitivity and uncertainty analysis further explores the effect of varying labour costs, feedstock price and the discount rate for both scenarios.

In *Scenario NG*, the following variables are varied in the sensitivity analysis, namely: the discount rate, cost of labour and feedstock price. Additionally, the investment costs are varied by including or excluding a chainsaw instead of an axe in the initial investment. Table 14 presents the results of this analysis. If the chainsaw is not included in the initial investment, then the NPV increases by the chainsaw price of 120 €. When doubling and tripling the discount rate in the analysis, the NPV declines significantly but remains positive. The NPV is more than halved when assuming a discount rate of 15%. Assuming no wage is paid for labour, results in the highest obtained NPV for *Scenario NG*. Varying labour-costs, the NPV becomes negative when the costs reach 0.26 €/labour-day. When including a feedstock price, the NPV is negative when the cost exceeds 3.3 €/m^3 (moisture content 50%) for feedstock.

Table 14. Combined sensitivity and uncertainty analysis of the NPV for charcoal production in *Scenario NG*.

	Discount rate	Labour costs	Raw material costs	Investment costs	NPV

	%	€/labourday	€/m3	€	€
Base case	5%	0.14	0	with chainsaw	683.95
Without chainsaw	5%	0.14	0	without chainsaw	803.95
Double discount	10%	0.14	0	with chainsaw	444.52
Triple discount	15%	0.14	0	with chainsaw	292.74
No labour	5%	0	0	with chainsaw	1480.52
Half labour	5%	1.25	0	with chainsaw	-5,631.77
Minimum labour	5%	2.5	0	with chainsaw	-12,738.66
Low feedstock price	5%	0.14	2	with chainsaw	-1,396.07
Medium feedstock price	5%	0.14	4	with chainsaw	-3,476.09
High feedstock price	5%	0.14	8	with chainsaw	-7,636.13

Table 15 shows the sensitivity analysis for the NPV of *Scenario EU*. If the feedstock price goes above 34 €/tonne dry wood the NPV becomes negative. The charcoal producer sales price also has a big effect on the NPV, the assumed sales price is relatively high compared to Reumerman & Frederiks (2002): 250 €/tonne charcoal. Assuming this price results in a negative NPV, making charcoal production in Finland economically unviable. In fact, when the charcoal sales price for the producer drops below 363 €, the NPV becomes negative. When varying the discount rate between 3% and 10% the NPV remains positive, until it reaches a discount rate above 16%. Lastly, the operation and maintenance [O&M] costs were examined, when these are increased by 50%, the NPV is still positive, although relatively low. Overall, the results are sensitive to the assumptions made in the methodology.

Table 15. Combined sensitivity and uncertainty analysis of the NPV for charcoal production in *Scenario EU*.

	Discount rate	**O&M**	**Charcoal sales price**	**Raw material costs**	**NPV**
	%	%	€/tonne	€/tonne green wood	€
Base case	9.5%	10%	400	28	197,390
Low discount rate	3.0%	10%	400	28	489,453
High discount rate	10.0%	10%	400	28	179,977
Low O&M	9.5%	5%	400	28	391,131
High O&M	9.5%	15%	400	28	3,649
Low production sales price	9.5%	10%	300	28	-325,352
High production sales price	9.5%	10%	500	28	720,132
Low feedstock price	9.5%	10%	400	20	452,732
High feedstock price	9.5%	10%	400	36	-54,169
Low investment costs	9.5%	10%	400	28	420,616
High investment costs	9.5%	10%	400	28	-25,836

5.4 Preventing unsustainable charcoal from Nigeria

It is confirmed in this research that the imported charcoal from Nigeria is unsustainable and has a much lower import price than importing intra-EU charcoal, therefore, measurements the EU could implement to prevent unsustainable charcoal from Nigeria are discussed in this section. First, all the previous results are interpreted and summarised. Then, previous policies concerning the EU's charcoal import are investigated, subsequently, policy recommendations are suggested to shift the import from unsustainable Nigerian charcoal to sustainably produced charcoal in the EU.

5.4.1 Interpretation

This research confirms that charcoal imported by the EU from Nigeria is unsustainably produced, emitting 284 g CO_2-eq/MJ. This GWP is 10 times higher than the GWP of sustainably produced charcoal in the EU, namely 20.3 g CO_2-eq/MJ. In 2016, the EU's charcoal import quantity from Nigeria is 147 ktonnes, as derived in the TDC. Assuming that the LHV of charcoal is 30.0 MJ/kg, this import contains a total of $4.40 \cdot 10^9$ MJ. Thus, the EU's charcoal import in 2016 caused 1.25 Mtonnes CO_2-eq/MJ. A total of 1.16 Mtonnes CO_2-eq could be mitigated annually by importing sustainably produced charcoal from the EU instead of importing unsustainable charcoal from Nigeria. Table 16 gives an overview of the associated GHG emissions of charcoal production per scenario.

Table 16. Associated GHG emissions of the amount of currently imported Nigerian charcoal.

Parameter	Unit	*Scenario NG*	*Scenario EU*	Difference
GHG emissions MJ	*g CO_2-eq/MJ*	284	20.3	264
Annual GHG emissions	*tonne CO_2-eq/year*	$1.25 \cdot 10^6$	$8.94 \cdot 10^4$	$1.16 \cdot 10^6$

The EU's import price for Nigerian charcoal is 229 €/tonne and the average intra-EU import price is more than double as high, namely 530 €/tonne. When converted to GJ assuming the LHV of charcoal, this results in 7.63 €/GJ and 17.7 €/GJ, see Table 17. Note that not all charcoal produced in the EU is sustainable, therefore this import price does not completely represent sustainable charcoal. In Nigeria, charcoal is sold at a production price below its true value, therefore, charcoal producers are forced to employ 'free labour' and acquire feedstocks illegally. Making it possible to export charcoal at an extremely low price.

Table 17. Cost structure for both scenarios.

Parameter	Unit	*Scenario NG*	*Scenario EU*	Difference
EU's import price, GJ	*€/GJ*	7.63	17.7	10.0
Production costs	*€/GJ*	0.70	10.6	9.91

5.4.2 Previous policy implementations

The environmental issues and concerns surrounding the Nigerian charcoal sector are also acknowledged by the EU. In 2013, a press release announced to financially support renewable energy policy in Nigeria in order to decrease the use of polluting traditional energy sources such as charcoal (European Commission, 2013). The press release also pointed to the consequences of traditional charcoal production for health and the environment, among other things the problem of deforestation in Nigeria. While the EU financially supports Nigerian renewable energy policy, imports of Nigerian charcoal to the EU have increased, contributing to the negative effects associated to charcoal production in Nigeria. In addition, as mentioned in the newspaper article by Hilse (2017), there exists loophole in the European Timber Regulation: "The regulation came into force in 2013 and was established to stop illegal wood and paper products from entering the EU. But while tropical woods are tightly regulated, charcoal does not even appear in the paper."

In 2007, the European Parliament attempted to ban charcoal imports from countries without legislation on replantation (European Parliament, 2008). The petition was proposed by the German Rafael Schiel. Despite the petitioner's concern "The Commission does not believe that there is sufficient evidence to suggest that an import ban on charcoal would redress the problem [...]"(European Parliament, 2008, p. 2). However, new steps have been taken through the FLEGT Action Plan to fight against illegal logging by supporting governance in the concerning countries. The FLEGT Action Plan was established in 2003 and meanwhile they also have projects in Nigeria to stop illegal logging.[18] Banning African charcoal in the EU has been tried before and did not succeed. Therefore, other perspectives to tackle this problem need to be considered.

5.4.3 Policy recommendations for the EU

All over the world different policy methods have been implemented to reduce GHG emissions (Lin & Li, 2011). One of these methods is carbon taxing, which is a cost-effective instrument in achieving a given abatement target. This policy is highly recommended by economists and international organisations (Lin & Li, 2011). Carbon taxes deal with the environmental costs, by including it into the total costs. Since carbon tax is one type of consumption tax depending on the

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[18] More about the Flegt Action Plan can be found on their website (European Forest Institute, 2017).

carbon content or CO_2 emissions of fossil fuels, it focuses ultimately on the reduction of CO_2 emissions (Lin & Li, 2011).

Assuming the previous identified EU's import prices for Nigerian charcoal and intra-EU charcoal, Table 18 illustrates the effect differing tax-amounts, in € per tonne CO_2, has on the initial import prices. With a carbon tax of 50 €/tonne CO_2 applying to both scenarios, the EU's import price for Nigerian charcoal than becomes 21.9 €/GJ, making intra-EU prices competitive, which now result in 18.7 €/GJ. Therefore, this research recommends charging a carbon-tax for importing charcoal.

Table 18. Influence on EU's import prices for Nigerian and intra-EU charcoal including a CO_2 tax.

Parameter	Unit	Value			
		0 €/t CO_2	*10 €/t CO_2*	*30 €/t CO_2*	*50 €/t CO_2*
Nigerian charcoal	*€/GJ charcoal*	7.63	10.5	16.2	21.9
Intra-EU charcoal	*€/GJ charcoal*	17.7	17.9	18.3	18.7

The question remains whether a carbon-tax will work better in practice than a charcoal ban; however, this goes beyond the purpose of this thesis and could be investigated in further research.

Other measurements could be to subsidise sustainable charcoal or tightening the certification rules. However, the latter is a complex situation, since it is recognised that on the EU's market the selling of charcoal from illegally harvested timber as FSC-certified charcoal occurs (Crumley, 2017). First, the charcoal is imported form a country without FSC-certified forests, such as Nigeria. Then, in the EU it is repacked and sometimes mixed, finally it is sold as FSC-certified charcoal produced within Europe. This issue should also be addressed by policy.

Finally, the biggest changes could probably be made in Nigeria. However, this is not the scope of this research. As mentioned in the "Introduction", multiple reports focus on improving the charcoal sector in SSA.[19] These reports could be consulted to apply measurements to improve the Nigerian charcoal sector, since there is room for improvement in Nigeria in terms of policy. Increased regulation and governance of the charcoal sector would result in increased tax income for governments and would increase the charcoal price to better reflect its true economic value. This increase in price will naturally result in higher prices to local consumers, but ultimately stimulate investments to increase production efficiency. In the past, also in Nigeria there has been an attempt to stop charcoal exports. The Nigerian government has tried to ban charcoal export in

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[19]: the World Agroforestry Centre reported the key areas where interventions are needed (Neufeldt et al., 2015), NL Agency assessed bottlenecks with possible solutions (Vos & Vis, 2010), and the World Future Council's focus was on policy solutions (Neuberger, 2015).

2013, as already mentioned in the “Case study”. However, in the same year the Charcoal Development Dealers Association has succeeded to lift the ban (Johnson, 2016). Today, charcoal imports from Nigeria continue while their production circumstances remain the same. Clearly, the attempts to solve the problem locally have not been fruitful. That is why the EU has to do something, such as implementing a carbon tax, if they want to stop the imports of unsustainable charcoal that contributes to deforestation, large amounts of GHG emissions and unfair wages.

6. Discussion

In the discussion, the limitations and uncertainties are elaborated on. First, regarding the data quality, followed by the case studies and methodology. Afterwards, the research validity is explored. Finally, an initiative to reduce unsustainable charcoal imports in the EU by a non-governmental organisation is discussed.

6.1 Uncertainty and limitations

Despite the uncertainties and limitations discussed in this section, this research serves as a guideline and approximate analysis that is adequate to answer the proposed research questions. In this section, first, the uncertainty and limitations regarding data quality are elaborated on. Then, the assumptions of the case studies and methodology are discussed.

6.1.1 Data quality

The consulted trade databases have to been dealt with carefully, since they probably do not always reflect exact reality. Therefore, not only one, but multiple trade databases are consulted in this research to increase reliability.

Secondary literature is used to acquire the necessary data for this research. In order to be as specific as possible, it is best to use recently published literature. However, sometimes old data sources are used, even from the 80s and 90s. These old sources are mostly used to collect the data for *Scenario NG*. Not much has changed over the years about the traditional production method, which is already used for many years. In order to collect the country specific data for both scenarios, grey literature is used: newspaper articles, reports and company websites. Especially for *Scenario NG*, and in particular for the EA, many of these grey sources have been consulted in order to collect all necessary data. Of course, first peer reviewed literature is considered, but when literature was not available the other sources were consulted. Finally, country specific was not always available, therefore, non-country specific data, such as general data on SSA, and data from other countries is used in some cases.

The assumptions made in the cost-benefit analysis are based on data from different periods in time and are not always country-specific. These values are adjusted for inflation and foreign exchange rates to get the most complete picture. Despite the values not always being time- and country-specific, the results of the analysis show a clear difference in the cost structure between both scenarios and is sufficient for this research. The reliability of the results can be improved by collecting primary data from an actual commercial industrial kiln.

In order to avoid previous mentioned inaccuracies, data from primary sources has to be collected. However, primary data collection for *Scenario NG* would still be difficult, because the charcoal sector is unregulated and partly illegal in Nigeria (Daramola & Ayeni, 2016). Therefore, data will probably hard to require, also on the spot. For the EA, company data, such as profit margins, are hard to obtain as this data is often kept secret. This is likely also the reason that this data could hardly be found in scientific literature.

6.1.2 Case study

This research only considers charcoal produced from woody biomass, but disregards briquettes that can be made from alternative feedstocks, such as coconut, bamboo or agricultural residues. Previous research already looked into the potential of alternative feedstocks. According to Vis et al. (2013), there is a high technical potential for alternative feedstocks such as cotton stalks in Nigeria, accounting for 1.3 Mtonnes per year. Also, research exists with a focus on bamboo as a suitable alternative for charcoal production within Africa.

In *Scenario EU* only harvest residues are included as feedstock. In a follow-up study, other feedstock inputs, such as industrial residues could be considered. The conversion process considered in *Scenario EU* is slow-pyrolysis. As mentioned in the "Case study", the choice for slow-pyrolysis is due to it having the highest charcoal yield. Further research could consider looking at fast pyrolysis, where bio-oil and syngas are produced primarily and charcoal is a by-product, or flash pyrolysis can be considered (Van Wesenbeeck et al., 2016). The syngas can be sold or substitute natural gas for heat applications (Brown et al., 2011).

It is assumed that all charcoal consumed in the EU is shipped to the Netherlands and consumed there. This is of course not the real situation. However, transportation is only 3% of the total emissions in *Scenario NG,* however 12% of the GWP of *Scenario EU*. The emissions of transport are a significant part of the total GWP of *Scenario EU* and changing the transportation distance can therefore affect the results of *Scenario EU*. Still this would not influence the ultimate outcome of this research, namely that *Scenario NG* has a much higher GWP than *Scenario EU*.

6.1.3 Methodology

To calculate the GWP within this research, three direct GHGs are taken into account: CO_2, CH_4 and N_2O. However, during incomplete combustion of biomass, also other pollutants are released, such as carbon monoxide [CO] and non-methane hydrocarbons [NMHC]. These two pollutants have an indirect effect on global warming (Smith et al., 1999). The impact of these indirect GHGs could be included in a follow-up research. However, these have almost not been studied yet. In addition, to the knowledge of the author, little research has been done on non-methane volatile organic compounds [NMVOCs], therefore this research does not take these GHG emissions into account. Further research is needed to increase the understanding of NMVOCs.

The LCA conducted in this research only considers a single environmental impact category, namely GWP. This does not give a complete picture of the overall environmental impact. In order to create a complete picture, other impact categories have to be included, such as human toxicity and resource depletion. These two impacts are already discussed in more detail below.

Firstly, several studies already examined the impact of charcoal production and consumption on human health. Abdel-Shafy and Mansour (2016) discusses the impact of polycyclic hydrocarbons caused by incomplete combustion on the human. The study from Olujimi et al. (2016) showed that charcoal workers are exposed to high levels of CO and particular matter with a diameter less than 2.5 micrometres [PM2.5]. Also, Table 1 in the "Theoretical background" illustrates that traditional kilns release more CO, a highly toxic emission for humans, than industrial kilns. This implies that it is beneficial for human health to use industrial kilns instead of traditional kilns.

Secondly, as mentioned in the "Case study", charcoal production in Nigeria contributes to deforestation (resource depletion), however, how much of the deforestation can exactly be attributed to charcoal production is still debated. As the mass balances show, Table 6 and Table 7 in the "Methodology", for *Scenario NG* to produce 1 tonne of charcoal for the end-use stage 15 tonnes of dry wood is needed (assuming green wood is carbonised). This means that for the 147 ktonnes charcoal imported by the EU from Nigeria in 2016, 2.20 Mtonnes dry wood is needed. Assuming a dry matter aboveground biomass of 184 tonnes per hectare (Nabuurs et al., 2004) and as Fadare (2017) suggests, replanting does not occur in Nigeria: 11,962 ha of forest has to be cut for the yearly amount of imported by the EU. A more optimistic replanting scenario, as suggested by Adeniji et al. (2015), assumes that 24% of the charcoal producers replant trees after harvesting. This scenario suggests that around 9,091 ha is cut down for the yearly EU's charcoal import from Nigeria. Assuming an average deforestation rate of 375,000 ha per year (Olasupo, 2016), the EU's charcoal import contributes to 3.19% of the annual Nigerian deforestation under the assumption of no replanting, and 2.42% when assuming 24% of the trees is replanted. When it is assumed that air dried wood with a moisture content of 15% (dry basis) is carbonised the percentages contributing to deforestation are more than halved (Table 19). This shows the importance of air-drying the woody biomass before carbonisation or improving the efficiency by changing towards a more efficient kiln, because less woody biomass is needed then. While this method is somewhat short-sighted and does not take into account natural forest regeneration, it becomes clear that the EU's import of Nigerian charcoal puts pressure on Nigerian forests. A more elaborate research is needed to investigate the deforestation caused by EU's charcoal import.

Table 19. Deforestation caused by the EU's import of Nigerian charcoal.

Parameter	Unit	No replanting	Partly replanting
Green wood input			
Harvested area	*ha/year*	11,961.64	9,090.85
Share total deforestation	*%/year*	3.19%	2.42%
Air-dried wood input			
Harvested area	*ha/year*	4,491.20	3,413.31
Share total deforestation	*%/year*	1.20%	0.91%

6.2 Research validity

This research looked at the EU's charcoal import from Nigeria, however Nigeria is not the only charcoal supplier of the EU. In 2016, Ukraine, Cuba, Paraguay, Namibia, Indonesia, Argentina, together with Nigeria, contributed nearly 358 ktonnes of charcoal to the EU (EC, 2017). However, what is known is that African charcoal is rarely FSC-certified, with an exception for South Africa (Vos & Vis, 2010). For example, Namibia is one of the biggest suppliers for the UK and the Namibian charcoal sector is also associated with illegal harvesting (Bawden, 2015). When making the rough assumption that these 358 ktonnes are all produced as unsustainable as in Nigeria, this results in a total GHG emissions of 3.06 Mtonnes CO_2-eq, with a possible mitigation of 2.84 Mtonnes CO_2-eq when shifting to importing sustainably produced charcoal from the EU.

The trade flows to the EU is only a small part of the global charcoal trade. Globally, Indonesia is the biggest charcoal exporter, and Brazil is the biggest producer of charcoal. Both these countries suffer high annual deforestation rates, partly caused by charcoal production (Van Wesenbeeck, 2016). The findings of this research cannot directly be applied to other trade flows; however, this research gives an indication of the associated GWP when unsustainable charcoal is traded.

6.3 Other initiatives

Several years ago, the non-profit organisation the Tropical Forest Trust [TFT], identified that around 40% of the charcoal sold in France was imported from Nigeria (Girard, 2015). The mission of the organisation is to bring total transparency in, among others, the charcoal sector. In 2013, they started their operations in France, where they traced back the charcoal to the wood source to ensure there are no links to deforestation to create awareness of the charcoal’s origin (TFT, n.d.). Between 2014 and 2016, the amount of Nigerian charcoal imported by France steadily decreased from 23 ktonnes to 5 ktonnes (ITC, 2017). Recently, they expanded their operations to Germany. This is a good initiative to create awareness and transparency about the charcoal origin and should be takes as an example for more countries in the EU.

7. Conclusion

The unregulated charcoal sector in Nigeria is associated with uncontrolled (illegal) harvesting and the use of inefficient traditional production methods. In 2016, the European Union [EU] imported nearly 147 ktonnes of charcoal from Nigeria. Between 2003 and 2016 imports from Nigeria to the EU have increased more than five-fold. No articles were found that cover the impact of the emissions caused by the EU's import of Nigerian charcoal, also the cost structure of Nigerian charcoal has not been compared to charcoal from the EU. The aim of this research is to fill this gap and explore the effects of shifting the EU's import of Nigerian charcoal to sustainably produced charcoal in the EU. This research answers the following two main research questions:
1. How much greenhouse gas emissions caused by the European Union's import of Nigerian charcoal may be mitigated by shifting production to the European Union?
2. *How economically feasible is it for the European Union to shift imports from Nigerian charcoal to sustainably produced charcoal in the European Union?*

In this research, two scenarios are studies. In the first scenario, *Scenario NG*, the charcoal is produced in Nigeria and in the second scenario, *Scenario EU*, the charcoal is produced within the EU, specifically Finland, while in both scenarios the charcoal is transported to and consumed in the Netherlands. *Scenario NG* represents the current situation of charcoal production in Nigeria and its export to the EU. *Scenario EU* is a representation of sustainable charcoal production using state-of-the-art technology.

To answer the research questions, three analyses are performed on the aforementioned scenarios. First, a trade database comparison [TDC] to map the EU's charcoal import. Second, a single-impact life cycle assessment [LCA], also called a carbon footprint, to determine the global warming potential [GWP] in gram CO_2 equivalent per MJ charcoal combusted in the end-use stage. Finally, an economic analysis [EA] calculates the production costs and benefits, together with the net present value [NPV].

The results reveal that around 1.16 Mtonnes CO_2-eq could be mitigated annually by importing sustainably produced charcoal from the EU instead of importing unsustainable charcoal from Nigeria, answering the first main research question. This answer was derived through combining its three sub-questions.

To answer sub-question 1a, the TDC was conducted. It was found that the EU imported around 147 ktonnes of charcoal from Nigeria for 34 M€ in 2016. Then, as calculated in the LCA the GWP of *Scenario NG* is 284 g CO_2-eq/MJ. Combined with the EU's charcoal import quantity from Nigeria, sub-question 1b is answered. The annually emitted GHG emissions by the EU's import of charcoal from Nigeria is 1.25 Mtonnes CO_2-eq.[20]

Next, the GWP for *Scenario EU* is approximated, 20.3 g CO_2-eq/MJ, and this is compared to *Scenario NG*, resulting in 284 g CO_2-eq/MJ. To answer sub-question 1c, the difference in GHG emissions per MJ charcoal consumed in the end-use stage between importing unsustainable charcoal from Nigeria and importing sustainably produced charcoal from the EU is 264 g CO_2-eq. This is caused by unsustainable harvesting and the use of traditional production methods in *Scenario NG*, compared to sustainable forestry and efficient production methods of *Scenario EU*.

The answer from the second main research question shows that it is currently not feasible to shift the EU's import from unsustainable charcoal from Nigeria to sustainably produced charcoal in the EU. The EU's import price for Nigerian charcoal is 7.63 €/GJ and lies below the production costs of sustainably produced charcoal in the EU, namely 10.6 €/GJ. In other words, sustainable charcoal cannot compete with cheap unsustainable charcoal without external support. Either the EU's import prices for Nigerian charcoal have to go up, or intra-EU import prices for charcoal need to go down. However, the latter is currently economically infeasible due to the high production costs for sustainable charcoal. Therefore, Nigerian charcoal prices have to go up.

To answer sub-question 2a, the import prices for charcoal are approximated through a trade database comparison. The EU's import price for Nigerian charcoal is 7.63 €/GJ, while the average intra-EU import price is 17.7 €/GJ[21].

Next, the difference in production costs was analysed through a cost-benefit analysis, answering sub-question 2b. The production costs for Nigerian charcoal amount to 0.70 €/GJ, is sold by the producer for 1.37 €/GJ, resulting in an NPV of 684 €. Charcoal production in Nigeria is only economically viable when labour costs are minimal and the feedstock is obtained for free. Nigerian charcoal is sold below its true market value creating a vicious circle of unregulated harvesting and inefficient production. The production costs for sustainably produced charcoal in the EU was much higher, namely around 10.6 €/GJ. This large difference in production costs is caused by the fact

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[20] Assuming the lower heating value of charcoal to be 30 MJ/kg.

[21] Note that not all charcoal produced in the EU is sustainable, therefore this import price does not completely represent sustainable charcoal.

that in Nigeria investments are minimal, while in the EU, feedstock is paid for and industrial kilns require a relatively high initial investment. If the producer sells the sustainable charcoal for 13.3 €/GJ, the NPV would be 197 k€.

This research suggests the following measure to prevent the import of cheap unsustainable charcoal from Nigeria and stimulate import of sustainably produced charcoal: a carbon tax of 50 €/tonne CO_2. This carbon tax will cause the import price for Nigerian charcoal to become higher than the intra-EU charcoal import price, respectively, 21.9 €/GJ and 18.7 €/GJ. Charcoal from the EU can then compete on price with Nigerian charcoal.

While the possible mitigation of GHG emissions when shifting the import from Nigerian charcoal to sustainably produced charcoal in the EU will not save the world, this research shows that the EU's import of Nigerian charcoal contributes to the vicious circle of the Nigerian charcoal sector and puts extra pressure on Nigerian forests. This specific case study is not directly applicable to other charcoal trade flow from developing countries. However, in many developing countries a similar situation regarding an unregulated charcoal sector is occurring. Therefore, this research serves as a basis for future studies on different regions.

Bibliography

Abasiryu, T., Ayuba, A., & Zira, A. E. (2016). Performance ealuation of some locally fabricated cookstoves in Mubi, Adamawa State, Nigeria. *Nigerian Journal of Technology*, *35*(1), 48. https://doi.org/10.4314/njt.v35i1.8

Abdel-Shafy, H. I., & Mansour, M. S. M. (2016). A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egyptian Journal of Petroleum*, *25*(1), 107–123. https://doi.org/10.1016/J.EJPE.2015.03.011

Abutu, A. (2011, December 8). Nigeria: Federal Government Loses N1 Billion to Illegal Charcoal, Wood Export. *Daily Trust*. Retrieved from http://allafrica.com/stories/201112080237.html

Adedeji, G. A., Ogunsanwo, O. Y., & John, J. (2013). Density Variations in Red Mangrove (Rhizophora racemosa GFW Meyer) in Onne, River State, Nigeria. *International Journal of Science and Nature*, *4*(1), 165–168. Retrieved from http://www.scienceandnature.org/IJSN_Vol4(1)M2013/IJSN-VOL4(1)13-29.pdf

Adeniji, O. A., Zaccheaus, O. S., Ojo, B. S., & Adedeji, A. S. (2015). Charcoal Production and Producers' Tree Species Preference in Borgu Local Government Area of Niger State, Nigeria. *Journal of Energy Technologies and Policy*, *5*(11), 1–8.

Adewole, N. A., & Oladejo, K. O. (2016). Charcoal Yield from Urban-Tree Residues Generated in University of Ibadan, Nigeria using Earth Mound Method. *International Journal of Energy Engineering*, *6*(2), 32–35. https://doi.org/10.5923/j.ijee.20160602.02

Aiyeloja, A. A., & Chima, U. D. (2011). Economic and ecological consequences of charcoal production in Oyo State, Nigeria. *Asia-Pacific Journal of Rural Development*, *21*(1), 85–92. Retrieved from https://www.researchgate.net/publication/266389111_Economic_and_ecological_consequences_of_charcoal_production_in_Oyo_State_Nigeria

Akyüz, K. C., & Balaban, Y. (2011). Wood fuel trade in European Union. *Biomass and Bioenergy*, *35*(4), 1588–1599. https://doi.org/10.1016/J.BIOMBIOE.2010.12.045

Anderson, N. M., Bergman, R. D., & Page-Dumroese, D. S. (2016). A Supply Chain Approach to Biochar Systems. In *Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation* (pp. 25–46). Cambridge University Press. Retrieved from https://books.google.nl/books?id=YQdQDQAAQBAJ&pg=PA27&lpg=PA27&dq=anderson+charcoal+supply+chain+biomass+production&source=bl&ots=syI7Hi9BuZ&sig=3GBW0JPX1LHwUz0XmcQ45h8WKyA&hl=en&sa=X&ved=0ahUKEwjUrL-j-oLZAhVCDcAKHSGZDLYQ6AEIPDAF#v=onepage&q=anderson ch

Anozie, A. N., Bakare, A. R., Sonibare, J. A., & Oyebisi, T. O. (2007). Evaluation of cooking energy cost, efficiency, impact on air pollution and policy in Nigeria. *Energy*, *32*(7), 1283–1290. https://doi.org/10.1016/j.energy.2006.07.004

Antal, M. J., & Grønli, M. (2003). The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research*, *42*(8), 1619–1640. https://doi.org/10.1021/ie0207919

Antal, M. J., Mok, W. S. L., Varhegyi, G., & Szekely, T. (1990). Review of methods for improving the yield of charcoal from biomass. *Energy & Fuels*, *4*(3), 221–225. https://doi.org/10.1021/ef00021a001

Babalola, F. D., & Opii, E. E. (2012). Factors influencing consumption of charcoal as household energy in

Benue State, Nigeria. *International Journal of Organic Agriculture Research and Development*, *6*, 68–81. Retrieved from https://www.researchgate.net/publication/282152027_Factors_influencing_consumption_of_charcoal_as_household_energy_in_Benue_State_Nigeria

Baccini, A. G. S. J., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., … Houghton, R. A. (2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, *2*(3), 182–185. https://doi.org/10.1038/nclimate1354

Bailis, R., Drigo, R., Ghilardi, A., & Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*(3), 266–272. https://doi.org/10.1038/nclimate2491

Baumann, H., & Tillman, A. M. (2004). *The hitchhiker's guide to LCA, an orientation in life cycle assessment methodology and application*. Sweden.

Bawden, T. (2015, August 9). How Namibian charcoal workers pay a high price for the cheap British barbecue. *The Independent*. Retrieved from https://www.independent.co.uk/life-style/food-and-drink/news/how-namibian-charcoal-workers-pay-a-high-price-for-the-cheap-british-barbecue-10446793.html

Bello, A. ;, & Jimoh. (2018). Some Physical and Mechanical Properties of African Birch (Anogeissus Leiocarpus) Timber. *J. Appl. Sci. Environ. Manage. January*, *22*(1), 79–84. https://doi.org/10.4314/jasem.v22i1.14

Ben-Iwo, J., Manovic, V., & Longhurst, P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. *Renewable and Sustainable Energy Reviews*, *63*, 172–192. https://doi.org/10.1016/j.rser.2016.05.050

Benjaafar, S., Li, Y., & Daskin, M. (2013). Carbon footprint and the management of supply chains: Insights from simple models. *IEEE Transactions on Automation Science and Engineering*, *10*(1), 99–116. https://doi.org/10.1109/TASE.2012.2203304

Blok, K., & Nieuwlaar, E. (2016). *Introduction to energy analysis* (2nd ed.). Taylor & Francis.

Bosner, A., Poršinsky, T., & Stankić, I. (2012). Forestry and life cycle assessment. In *Global perspectives on sustainable forest management*. InTech. https://doi.org/10.5772/32898

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining*, *5*(1), 54–68. https://doi.org/10.1002/bbb.254

Buhari, C. M. (2013). An analysis of Nigerian seaborne trade (dry bulk) and the demand for transport. *International Affairs and Global Strategy*, *15*, 13–47. Retrieved from http://www.iiste.org/Journals/index.php/IAGS/article/view/8015

Cargo Handbook. (2016). Charcoal. Retrieved November 2, 2017, from http://www.cargohandbook.com/index.php/Charcoal

Cellini, S. R., & Kee, J. E. (2015). Cost-effectiveness and cost-benefit analysis. In *Handbook of Practical Program Evaluation* (pp. 636–672). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119171386.ch24

Chidumayo, E. N., & Gumbo, D. J. (2013). The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. *Energy for Sustainable Development*, *17*(2), 86–94. https://doi.org/10.1016/j.esd.2012.07.004

Competition & Markets Authority. (2015). *Energy market investigation: Analysis of cost of capital of energy firms*. Retrieved from https://assets.publishing.service.gov.uk/media/54edfe9340f0b6142a000001/Cost_of_capital.pdf

Crumley, E. (2017). *Strengthening the FSC supply chain - Charcoal*. Retrieved from https://se.fsc.org/preview.charcoal-fact-sheet.a-1007.pdf

Daramola, A. O., & Ayeni, A. O. (2016). Appraisal of charcoal production drivers in Ibarapa Region, Oyo State, Nigeria. *International Journal of Renewable Energy and Environment*, *2*, 126–138. Retrieved from https://www.researchgate.net/publication/304657128_APPRAISAL_OF_CHARCOAL_PRODUCTION_DRIVERS_IN_IBARAPA_REGION_OYO_STATE_NIGERIA

Daystar, J., Gonzalez, R., Reeb, C., Venditti, R. A., Treasure, T., Abt, R., & Kelley, S. (2013). Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the southern US: Pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum. *BioResources*, *9*(1), 393–444. https://doi.org/10.15376/biores.9.1.393-444

de Miranda, R. C., Sepp, S., Ceccon, E., Mann, S., & Singh, B. (2010). *Sustainable production of commercial woodfuel: Lessons and guidance from two strategies*. Washington, D.C. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.720.8759&rep=rep1&type=pdf

Duku, M. H., Gu, S., & Hagan, E. Ben. (2011). Biochar production potential in Ghana—A review. *Renewable and Sustainable Energy Reviews*, *15*(8), 3539–3551. https://doi.org/10.1016/J.RSER.2011.05.010

EC. (2017). Market Access database: Statistics. Retrieved October 31, 2017, from http://madb.europa.eu/madb/statistical_form.htm

Ekeh, O., Fangmeier, A., & Müller, J. (2014). Quantifying greenhouse gases from the production, transportation and utilization of charcoal in developing countries: A case study of Kampala, Uganda. *The International Journal of Life Cycle Assessment*, *19*(9), 1643–1652. https://doi.org/10.1007/s11367-014-0765-7

Elijah, O. A., Balikis, L. I., & Ambali, O. I. (2017). Comparative Analysis of Access, and Preferences of Rural and Urban Households for Cooking Energy, and the Determinants in Nigeria: A Case of Ogun State. *Agricultura Tropica et Subtropica*, *50*(1), 45–53. https://doi.org/10.1515/ats-2017-0006

Emrich, W. (1985). End-Use Markets for Charcoal and Charcoal by-Products. In *Handbook of Charcoal Making* (pp. 178–207). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-0450-2_6

Eneji, I. S., Obinna, O., & Azua, E. T. (2014). Sequestration and Carbon Storage Potential of Tropical Forest Reserve and Tree Species Located within Benue State of Nigeria. *Journal of Geoscience and Environment Protection*, *2*(2), 157–166. https://doi.org/10.4236/gep.2014.22022

Eriksson, L. N. (2008). Comparative analyses of forest fuels in a life cycle perspective with a focus on transport systems. *Resources, Conservation and Recycling*, *52*(10), 1190–1197. https://doi.org/10.1016/J.RESCONREC.2008.06.009

Eriksson, O. (2007). Sensitivity and Uncertainty Analysis Methods, with Applications to a Road Traffic Emission Model. Retrieved from http://liu.diva-portal.org/smash/get/diva2:23145/FULLTEXT01.pdf

European Commission. (n.d.). *Woodfuel Harvesting*. Retrieved from https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/afo_woodfuel_harvesting_en.pdf

European Commission. (2013, July 4). New EU support for renewable energy policy in Nigeria. *Press Release*. Retrieved from http://europa.eu/rapid/press-release_IP-13-649_en.htm

European Commission. (2015). *The European Union leading in Renewables*. Retrieved from http://ec.europa.eu/energy/sites/ener/files/documents/cop21-brochure-web.pdf

European Forest Institute. (2017). EU FLEGT Action Plan. Retrieved January 10, 2018, from http://www.euflegt.efi.int/what-is-flegt

European Parliament. Notice to members, Pub. L. No. 0435/52007, 3 (2008). Retrieved from http://www.europarl.europa.eu/meetdocs/2004_2009/documents/cm/729/729457/729457en.pdf

Ezzati, M., & Kammen, D. M. (2002). The Health Impacts of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs. *Environmental Health Perspectives*, *110*(11). Retrieved from http://rael.berkeley.edu/old_drupal/sites/default/files/very-old-site/Ezzati-Kammen-EHP2002.pdf

Fadare, S. (2017, October 27). The forests... going, going and going. *The Nation Nigeria*. Retrieved from http://thenationonlineng.net/the-forests-going-going-going/

FAO. (1985). *Industrial charcoal making*. Rome, Italy: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/x5555e/x5555e00.htm#Contents

FAO. (1985). Raw materials for carbonisation. In *Industrial charcoal making*. Rome. Retrieved from http://www.fao.org/docrep/x5555e/x5555e05.htm#chapter 4. raw materials for carbonisation

FAO. (1985). Wood carbonisation and the products it yields. In *Industrial charcoal making*. Rome. Retrieved from http://www.fao.org/docrep/x5555e/x5555e03.htm

FAO. (1987). Transport, storage and distribution of charcoal. In *Simple technologies for charcoal making*. Rome, Italy: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/X5328e/x5328e00.htm#Contents

FAO. (2008). Industrial Charcoal Production. In J. Domac & M. Trossero (Eds.), *Development of a sustainable charcoal industry*. Zagreb, Croatia.

FAO Statistics. (2017). *Forest Products 2015 Yearbook*. Rome, Italy. Retrieved from http://www.fao.org/3/a-i7304m.pdf

FAOstat. (2017). Forestry Production and Trade. Retrieved September 7, 2017, from http://www.fao.org/faostat/en/#data/FO/visualize

Finnish Forest Association. (2014). Finnish forests resources. Retrieved January 5, 2018, from https://www.smy.fi/en/forest-fi/forest-facts/finnish-forests-resources/

Foley, G. (1986). *Charcoal making in developing countries* (5th ed.). London, United Kingdom: Earthscan/James & James.

Garcia-Nunez, J. A., Pelaez-Samaniego, M. R., Garcia-Perez, M. E., Fonts, I., Abrego, J., Westerhof, R. J. M., & Garcia-Perez, M. (2017). Historical Developments of Pyrolysis Reactors: A Review. *Energy & Fuels*, *31*(6), 5751–5775. https://doi.org/10.1021/acs.energyfuels.7b00641

Girard, F. (2015, April 16). Charcoal and Change. *Tropical Forest Trust*. Retrieved from http://www.tft-earth.org/stories/blog/charcoal-and-change/

Girard, P. (2002). Charcoal production and use in Africa: what future? *Unasylva*, *211*(53). Retrieved from http://www.fao.org/3/a-y4450e/y4450e05.pdf

Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2017). *Solid and gaseous bioenergy pathways: input values and GHG emissions*. https://doi.org/10.2790/27486

Gómez, D. R., Watterson, J. D., Americanohia, B. B., Ha, C., Marland, G., Matsika, E., … Treanton, K.

(2006). Chapter 2: Stationary Combustion. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://doi.org/10.1016/S0166-526X(06)47021-5

Gujba, H., Mulugetta, Y., & Azapagic, A. (2015). The household cooking sector in Nigeria: Environmental and economic sustainability assessment. *Resources*, *4*(2), 412–433. https://doi.org/10.3390/resources4020412

Hillring, B. (2006). World trade in forest products and wood fuel. *Biomass and Bioenergy*, *30*(10), 815–825. https://doi.org/10.1016/j.biombioe.2006.04.002

Hilse, G. (2017, December 23). Charcoal: exported by Africa, bought by Europe | Africa | DW | 23.12.2017. *DW*. Retrieved from http://www.dw.com/en/charcoal-exported-by-africa-bought-by-europe/a-41916123

Hoefnagels, R., Searcy, E., Kafferty, K., Cornelissen, T., Junginger, M., Jacobson, J., & Faaij, A. (2014). Lignocellulosic feedstock supply systems with intermodal and overseas transportation. *Biofuels, Bioproducts and Biorefining*, *8*(6), 794–818. https://doi.org/10.1002/bbb.1497

International Biochar Initiative. (2018). Biochar Production Units. Retrieved May 21, 2018, from http://www.biochar-international.org/technology/production

Investopedia. (2018). Cost-Benefit Analysis. Retrieved May 28, 2018, from https://www.investopedia.com/terms/c/cost-benefitanalysis.asp

ITC. (2017). Trade Map. Retrieved from https://www.trademap.org/Country_SelProduct_TS.aspx?nvpm=1%7C%7C%7C%7C%7CTOTAL%7C%7C%7C2%7C1%7C1%7C2%7C2%7C1%7C2%7C1%7C

Jamala, G. Y., Abraham, P., Joel, L., & Asongo, A. (2013). Socio-economic implications of charcoal production and marketing in Nigeria. *Journal of Agriculture and Veterinary Science*, *5*(4), 41–45. Retrieved from www.iosrjournals.org

Jelili, M. O., Saliu, I., & Falaye, A. (2015). Charcoal Production in Oriire Local Government Area, Oyo State, Nigeria: Environmental and Socio-Economic Questions. *Civil and Environmental Research*, *7*(12), 21–28. Retrieved from http://www.iiste.org/Journals/index.php/CER/article/view/27432

Johnson, E. (2009). Charcoal versus LPG grilling: A carbon-footprint comparison. *Environmental Impact Assessment Review*, *29*(6), 370–378. https://doi.org/10.1016/j.eiar.2009.02.004

Johnson, T. (2016, June 23). Lift ban on charcoal exportation. *The Nation Nigeria*. Retrieved from http://thenationonlineng.net/lift-ban-charcoal-exportation/

Jones, B. (2015). *Social and environmental impacts of charcoal production in Liberia*. University of Michigan. Retrieved from https://deepblue.lib.umich.edu/bitstream/handle/2027.42/110987/Brieland_Jones_Thesis_2015.pdf?sequence=1&isAllowed=y

Kammen, D. M., & Lew, D. J. (2005). *Review of Technologies for the Production and Use of Charcoal*. Retrieved from http://rael.berkeley.edu/old_drupal/sites/default/files/old-site-files/2005/Kammen-Lew-Charcoal-2005.pdf

Kituyi, E. (2004). Towards sustainable production and use of charcoal in Kenya: exploring the potential in life cycle management approach. *Journal of Cleaner Production*, *12*(8–10), 1047–1057. https://doi.org/10.1016/j.jclepro.2004.02.011

Klavina, K., Klavins, J., Veidenbergs, I., & Blumberga, D. (2016). Charcoal production in a continuous operation retort. Experimental data processing. *Energy Procedia*, *95*, 208–215. https://doi.org/10.1016/j.egypro.2016.09.051

Krajnc, N. (2015). *Wood Fuels Handbook*. Pristina, Kosovo. Retrieved from http://www.fao.org/3/a-i4441e.pdf

Kung, C.-C., McCarl, B. A., & Cao, X. (2013). Economics of pyrolysis-based energy production and biochar utilization: A case study in Taiwan. *Energy Policy*, *60*, 317–323. https://doi.org/10.1016/J.ENPOL.2013.05.029

Lacaux, J. P., Brocard, D., Lacaux, C., Delmas, R., Brou, A., Yoboué, V., & Koffi, M. (1994). Traditional charcoal making: an important source of atmospheric pollution in the African Tropics. *Atmospheric Research*, *35*(1), 71–76. https://doi.org/10.1016/0169-8095(94)90073-6

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, *3*(5), 547–562. https://doi.org/10.1002/bbb.169

Lehmann, J., Joseph, S., & (Eds.). (2015). *Biochar for environmental management: science, technology and implementation*. Routledge. Retrieved from https://books.google.nl/books/about/Biochar_for_Environmental_Management.html?id=5dkRbbVjpf8C&redir_esc=y

Leinonen, A. (2004). *Harvesting technology of forest residues for fuel in the USA and Finland*. Helsinki, Finland. Retrieved from http://www.vtt.fi/inf/pdf/

Li, H., Chen, Q., Zhang, X., Finney, K. N., Sharifi, V. N., & Swithenbank, J. (2012). Evaluation of a biomass drying process using waste heat from process industries: A case study. *Applied Thermal Engineering*, *35*, 71–80. https://doi.org/10.1016/j.applthermaleng.2011.10.009

Lin, B., & Li, X. (2011). The effect of carbon tax on per capita CO2 emissions. *Energy Policy*, *39*(9), 5137–5146. https://doi.org/10.1016/J.ENPOL.2011.05.050

Lindstad, H., Asbjørnslett, B. E., & Strømman, A. H. (2012). The importance of economies of scale for reductions in greenhouse gas emissions from shipping. *Energy Policy*, *46*, 386–398. https://doi.org/10.1016/J.ENPOL.2012.03.077

Luoga, E. J., Witkowski, E. T. F., & Balkwill, K. (2000). Economics of charcoal production in miombo woodlands of eastern Tanzania: some hidden costs associated with commercialization of the resources. *Ecological Economics*, *35*(2), 243–257. https://doi.org/10.1016/S0921-8009(00)00196-8

Mola-Yudego, B., Arevalo, J., Díaz-Yáñez, O., Dimitriou, I., Haapala, A., Carlos Ferraz Filho, A., … Valbuena, R. (2017). Wood biomass potentials for energy in northern Europe: Forest or plantations? *Biomass and Bioenergy*, *106*, 95–103. https://doi.org/10.1016/j.biombioe.2017.08.021

Mwampamba, T. H., Ghilardi, A., Sander, K., & Chaix, K. J. (2013). Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries. *Energy for Sustainable Development*, *17*(2), 75–85. https://doi.org/10.1016/j.esd.2013.01.001

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 659–740). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

Nabuurs, G. J., Ravindranath, N. H., Paustian, K., Freibauer, A., Hohenstein, W., Makundi, W., … Bickel, K. (2004). Annex 3A.1 Biomass Default Tables for Section 3.2 Forest Land - LUCF sector good practice guidance). In *Good practice guidance for land use, land use change and forestry*. Institute for Global Environmental Strategies (for the IPCC). Retrieved from http://www.ipcc.ch/meetings/session21/doc5to8/chapter3a1.pdf

Natural Resources Institute Finland. (2016). Tree species. Retrieved June 4, 2018, from https://www.luke.fi/en/natural-resources/forest/tree-species/

Neuberger, I. (2015). *Policy solutions for sustainable charcoal in Sub-Saharan Africa*. Hamburg. Retrieved from https://www.worldfuturecouncil.org/file/2016/01/WFC_2015_Policy_Handbook_Solutions_for_Sustainable_Charcoal_in_Sub-Saharan_Africa.pdf

Neufeldt, H., Langford, K., Fuller, J., Iiyama, M., & Dobie, P. (2015). *From transition fuel to viable energy source: improving sustainability in the sub-Saharan charcoal sector* (ICRAF Working Paper No. 196). Nairobi. https://doi.org/10.5716/wp15011.pdf

Njenga, M., Karanja, N., Karlsson, H., Jamnadass, R., Iiyama, M., Kithinji, J., & Sundberg, C. (2014). Additional cooking fuel supply and reduced global warming potential from recycling charcoal dust into charcoal briquette in Kenya. *Journal of Cleaner Production*, *81*, 81–88. https://doi.org/10.1016/J.JCLEPRO.2014.06.002

Notteboom, T. E. (2010). Concentration and the formation of multi-port gateway regions in the European container port system: an update. *Journal of Transport Geography*, *18*(4), 567–583. https://doi.org/10.1016/J.JTRANGEO.2010.03.003

Novus Agro. (2016). The charcoal industry is a multi-billion dollar industry. Retrieved June 4, 2018, from http://novusagro.com/the-charcoal-industry-is-a-multi-billion-dollar-industry/

Nsamba, H. K., Hale, S. E., Cornelissen, G., & Bachmann, R. T. (2015). Sustainable technologies for small-scale biochar production — A review. *Journal of Sustainable Bioenergy Systems*, *5*(1), 10–31. https://doi.org/10.4236/jsbs.2015.51002

Nwofe, P. (2013). Comparative analysis of domestic energy use in Nigeria — A review. *Continental Journal of Renewable Energy*, *4*(1), 7–17. https://doi.org/10.5707/cjre.2013.4.1.7.17

Ogunsanwo, O. Y., Aiyeloja, A. A., & Uzo, C. (2007). Production technique and the influence of wood species on the properties of charcoal in Nigeria, a case study of Oyo State. *Agricultural Journal*, *2*(1), 131–133. Retrieved from http://docsdrive.com/pdfs/medwelljournals/aj/2007/131-133.pdf

Olasupo, F. (2016, April 19). Nigeria loses about 350,000 to 400,000 hectares of land per year to deforestation – Report. *Vanguard News*. Retrieved from https://www.vanguardngr.com/2016/04/nigeria-loses-350000-400000-hectares-land-per-year-deforestation-report/

Olivier, J. G. J., Schure, K. M., & Peters, J. A. H. W. (2017). *Trends in global CO2 and total greenhouse gas emissions: 2017 Report*. The Hague. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2017-trends-in-global-co2-and-total-greenhouse-gas-emissons-2017-report_2674.pdf

Olsthoorn, K. (2006). Uitstoot van Broeikasgassen. *Energy Magazine*.

Openshaw, K. (1983). Measuring fuelwood and charcoal. In *Wood fuel surveys*. Rome. Retrieved from http://www.fao.org/docrep/Q1085E/q1085e0c.htm

Oritse, G. (2016, May 22). Federal Government bans wood, charcoal exportation. *Vanguard News*. Retrieved from https://www.vanguardngr.com/2016/05/fg-bans-wood-charcoal-exportation/

Pennise, D. M., Smith, K. R., Kithinji, J. P., Rezende, M. E., Raad, T. J., Zhang, J., & Fan, C. (2001). Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. *Journal of Geophysical Research: Atmospheres*, *106*(D20), 24143–24155.

https://doi.org/10.1029/2000jd000041

Ports. (2017). Sea route and distance. Retrieved November 2, 2017, from http://ports.com/sea-route/port-of-rotterdam,netherlands/port-of-lagos-apapa,nigeria/

Premium Times Nigeria. (2016, February 2). CBN agrees to 5% lending rate for farmers – Ogbeh. *Premium Times Nigeria*. Retrieved from https://www.premiumtimesng.com/business/business-news/197861-cbn-agrees-5-lending-rate-farmers-ogbeh.html

Reumerman, P. J., & Frederiks, B. (2002). Charcoal production with reduced emissions. *12th European Conference on Biomass for Energy, Industry and Climate Protection, Amsterdam*. Retrieved from http://www.cleanfuels.nl/Sitepdfs/Charcoal Production with Reduced Emissions (paper).pdf

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

Routa, J., Kellomäki, S., Kilpeläinen, A., Peltola, H., & Strandman, H. (2011). Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. *GCB Bioenergy*, *3*(6), 483–497. https://doi.org/10.1111/j.1757-1707.2011.01106.x

Routa, J., Pyörälä, P., Alam, A., Kilpeläinen, A., Peltola, H., & Kellomäki, S. (2013). Integrated production of timber and energy biomass in forestry. In . (Ed.), *Forest BioEnergy Production* (pp. 57–79). New York, NY: Springer, New York. https://doi.org/10.1007/978-1-4614-8391-5_4

Samojlik, T., Jędrzejewska, B., Michniewicz, M., Krasnodębski, D., Dulinicz, M., Olczak, H., … Rotherham, I. D. (2013). Tree species used for low-intensity production of charcoal and wood-tar in the 18th-century Białowieża Primeval Forest, Poland. *Phytocoenologia*, *43*(1), 1–12. https://doi.org/10.1127/0340-269X/2013/0043-0511

San Miguel, G., Méndez, A. M., Cascó, G., & Quero, A. (2017). LCA of alternative biochar production technologies. In *15th International Conference on Environmental Science and Technology*. Rhodes. Retrieved from https://cest.gnest.org/sites/default/files/presentation_file_list/cest2017_00937_oral_paper.pdf

Sander, K., Haider, S. W., & Hyseni, B. (2011). *Wood-Based Biomass Energy Development for Sub-Saharan Africa: Issues and Approaches*. Retrieved from https://siteresources.worldbank.org/EXTAFRREGTOPENERGY/Resources/717305-1266613906108/BiomassEnergyPaper_WEB_Zoomed75.pdf

Searcy, E., Hess, J. R., Tumuluru, J., Ovard, L., Muth, D. J., Trømborg, E., … Hoefnagels, R. (2014). Optimization of biomass transport and logistics. In *International Bioenergy Trade.* (pp. 103–123). Dordrecht: Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6982-3_5

Sedano, F., Silva, J. A., Machoco, R., Meque, C. H., Sitoe, A., Ribeiro, N., … Tucker, C. J. (2016). The impact of charcoal production on forest degradation: a case study in Tete, Mozambique. *Environmental Research Letters*, *11*(9), 1–12. https://doi.org/10.1088/1748-9326/11/9/094020

Seidel, A. (2008). *Charcoal in Africa: Importance, problems and possible solution strategies*. Eschborn. Retrieved from https://energypedia.info/images/2/22/Charcoal-in-africa-gtz_2008-eng.pdf

Serrano-Medrano, M., Arias-Chalico, T., Ghilardi, A., & Masera, O. (2014). Spatial and temporal projection of fuelwood and charcoal consumption in Mexico. *Energy for Sustainable Development*, *19*, 39–46. https://doi.org/10.1016/j.esd.2013.11.007

Smith, K. R., Pennise, D. M., Khummongkol, P., Chaiwong, V., Ritgeen, K., Zhang, J., … Thorneloe, S. . (1999). Greenhouse gases from small-scale combustion devices in developing countries: Charcoal-making kilns in Thailand. *US Environmental Protection Agency, Office of Research and*

Development. Retrieved from http://www.bioenergylists.org/stovesdoc/Smith/kilns.htm

Stassen, H. E. (2015). Current issues in charcoal production and use. In W. Swaaij, S. Kersten, & W. Paltz (Eds.), *Biomass Power for the World* (pp. 425–511). Pan Stanford Publishing. Retrieved from https://books.google.nl/books?hl=en&lr=&id=GJq9BwAAQBAJ&oi=fnd&pg=PA425&dq=reason+charcoal+consumption+Europe&ots=puCnT8OEAW&sig=sdGF_U6dWXkxK3MNCMdzMV44r5A#v=onepage&q&f=false

Steng. (n.d.). *A Life cycle Assessment (LCA) of Biomass Pyrolysis & Gasification*. Retrieved from http://www.e2bebis.eu/wp-content/uploads/2014/09/6-LCA-Biomass-Pyrolysis-AG2-pdf-16jul14.pdf

Suopajärvi, H., & Fabritius, T. (2013). Towards more sustainable ironmaking—An analysis of energy wood availability in finland and the economics of charcoal production. *Sustainability*, *5*(3), 1188–1207. https://doi.org/10.3390/su5031188

Svoboda, K., Martinec, J., Pohořelý, M., & Baxter, D. (2009). Integration of biomass drying with combustion/gasification technologies and minimization of emissions of organic compounds. *Chemical Papers*, *63*(1), 15–25. https://doi.org/10.2478/s11696-008-0080-5

Tahvanainen, T., & Anttila, P. (2011). Supply chain cost analysis of long-distance transportation of energy wood in Finland. *Biomass and Bioenergy*, *35*(8), 3360–3375. https://doi.org/10.1016/j.biombioe.2010.11.014

The Forest Trust. (n.d.). Charcoal. Retrieved May 23, 2018, from http://www.tft-transparency.org/product/charcoal/what-we-do/

Tran, K. Q., Alonso, M. Z., Wang, L., & Skreiberg, Ø. (2017). Simultaneously boosting the mass and fixed-carbon yields of charcoal from forest residue via atmospheric carbonization. *Energy Procedia*, *105*, 787–792. https://doi.org/10.1016/j.egypro.2017.03.390

Tunde, A., Adeleke, E., & Adeniyi, E. (2013). Impact of Charcoal Production on the Sustainable Development of Asa Local Government Area, Kwara State, Nigeria. *African Research Review*, *7*(2), 1–15. https://doi.org/10.4314/afrrev.v7i2.1

United Nations Environment Programme. (2015). *Annual Report 2014*. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/9420/-UNEP_2014_Annual_Report-2015UNEP_Annual_Report_2014_Production_LQ.pdf.pdf?sequence=3&isAllowed=y

United States Department of State. (2016). *Nigeria 2016 Human Rights Report*. Retrieved from https://www.state.gov/documents/organization/265500.pdf

Valente, C., Hillring, B. G., & Solberg, B. (2012). Greenhouse Gas Emissions, Energy Use, and Costs—Case Studies of Wood Fuel Supply Chains in Scandinavia. *International Journal of Forest Engineering*, *23*(2), 71–81. https://doi.org/10.1080/14942119.2012.10739963

Van Dam, J. (2017). *The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods*. Rome, Italy. Retrieved from http://www.fao.org/3/a-i6935e.pdf

Van Wesenbeeck, S., Wang, L., Ronsse, F., Prins, W., Skreiberg, Ø., & Antal Jr, M. J. (2016). Charcoal "Mines" in the Norwegian Woods. *Energy & Fuels*, *30*(10), 7959–7970. https://doi.org/10.1021/acs.energyfuels.6b00919

Vis, M., Uitdewillingen, L., & Vos, J. (2013). *Charcoal production from alternative feedstocks*. Retrieved from https://english.rvo.nl/sites/default/files/2013/12/Charcoal_production_from_alternative_feedstocks_-_June_2013.pdf

Vos, J., & Vis, M. (2010). *Making charcoal production in Sub Sahara Africa sustainable*. Utrecht, the

Netherlands. Retrieved from http://english.rvo.nl/sites/default/files/2013/12/Report Charcoal - BTG - NPSB_0.pdf

Whittaker, C., Mortimer, N., Murphy, R., & Matthews, R. (2011). Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass and Bioenergy*, *35*(11), 4581–4594. https://doi.org/10.1016/J.BIOMBIOE.2011.07.001

Wolf, M., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D., … Goralczyk, M. (2010). *ILCD Handbook-General Guide for Life Cycle Assessment-Detailed Guidance*. Publications Office of the European Union. https://doi.org/10.2788/38479

Work Green. (n.d.). Sustainable Forestry. Retrieved June 3, 2018, from http://www.workgreen.ca/content/sustainable-forestry

Zulu, L. C., & Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa. *Energy for Sustainable Development*, *17*(2), 127–137. https://doi.org/10.1016/J.ESD.2012.07.007

Appendices

Appendix A: Search terms for trade databases.

Table 20. Search terms for original data from the EC database for EU's charcoal import.

	from world	from Nigeria
Product	4402	4402
EU Member State	EU28	EU28
Partner country	All partners	Nigeria
Other criteria	Quantity/Value	Quantity/Value
Quantity	Euro	Euro
Value	Kg	Kg

Table 21. Search terms for original data from ITC database for EU's charcoal import.

	from world	from Nigeria	from intra-EU
Product	4402	4402	4402
Country/ Country group	European Union (EU28)	Nigeria	European Union (EU28)
Partner/ Partner group	All	European Union (EU28)	European Union (EU28)
Other criteria	Imports; Yearly time series; by importing country; Quantities/Values	Exports; Yearly time series; by country; Mirror data; Quantities/Values	Imports; Yearly time series; by product; Values
Quantity	Tonnes	Tonnes	- (Not available
Value	Euro thousand	Euro thousand	Euro thousand

* "Mirror data invert the reporting standards by valuing exports in CIF terms (i.e. including transportation and insurance costs) and imports in FOB terms (i.e. excluding these services)." (ITC, 2017).

Table 22. Search terms for original data from FAOstat database for EU's charcoal import.

	from world
Product	Wood charcoal
Special groups	European Union > (List)
Other criteria	Import Quantity/Import Value
Quantity	Tonnes
Value	US Dollar thousand

Appendix B: GWP data for *Scenario NG*

Table 23. Feedstock logistics *Scenario NG*.

FEEDSTOCK LOGISTICS				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data chainsaw				
Fuel consumption	FC	*kg/m3 wood*	0.25	a
Emission factor CO2	EF_{CO2}	*g CO2/kg fuel*	3,150	a
Emission factor CH4	EF_{CH4}	*g CH2/kg fuel*	6.91	a
Emission factor N2O	EF_{N2O}	*g N2O/kg fuel*	0.02	a
Calculations felling				
Wood density	WD	*kg/m3*	896	b
Emissions CO2	E_{CO2}	*g CO2/tonne wood*	878.91	c
Emissions CH4	E_{CH4}	*g CH4/tonne wood*	1.93	c
Emissions N2O	E_{N2O}	*g N2O/tonne wood*	0.01	c
Results feedstock logistics				
Felling	GWP felling	*g CO2-eq/tonne wood*	934	d
Sizing	GWP sizing	*g CO2-eq/tonne wood*	934	e

[a] The data for felling trees with a chainsaw is derived from Bosner et al. (2012) {Table 8}. From the three chainsaws given (C1 = Stihl 026; C2 = Stihl 036; C3 = Stihl 026/036) the average is calculated for fuel consumption and for the three emission factors. [b] The wood density assumed in this scenario is [896 kg/m^3] (Adedeji et al., 2013). [c] The emissions for felling are calculated with $E_x = EF_x * FC * 1000[kg]/WD$. [d] The GWP for felling is calculated using equation 1, notice the emissions are given per tonne wet wood 50% moisture content wet basis. Therefore, this value has to multiplied with 2 in order to get the emissions per tonne dry wood. [e] For sizing the same GWP is assumed as for felling.

Table 24. Conversion *Scenario NG*.

CONVERSION				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data low efficiency earth mound kiln				
Emission factor CO2	EF_{CO2}	*g CO2/kg charcoal*	2,510	f
Emission factor CH4	EF_{CH4}	*g CH2/kg charcoal*	40.7	f
Emission factor N2O	EF_{N2O}	*g N2O/kg charcoal*	0.21	f
Calculations carbonisation				
Emissions CO2	E_{CO2}	*g CO2/tonne charcoal*	2,510,000	g
Emissions CH4	E_{CH4}	*g CH4/tonne charcoal*	40,700	g
Emissions N2O	E_{N2O}	*g N2O/tonne charcoal*	210	g
Results conversion				
Conversion	GWP conversion	*g CO2-eq/tonne charcoal*	3,705,250	h

[f] The emission factors for charcoal production [g pollutant/kg charcoal produced] originate from Njenga et al. (2014) {Table 1}. Njenga et al. (2014) took the average of two traditional earth mound kilns in Kenya, EM1 and EM2, with a kiln efficiency of 22% (Pennise et al., 2001). [g] The emission factors are converted from [g EF/kg charcoal produced] to emissions [g E_{GHG}/tonne charcoal produced]. [h] The GWP for conversion is calculated using equation 1, as the biomass is harvested unsustainable, the biogenic CO_2 released is included within this calculation.

Table 25. Distribution logistics *Scenario NG*.

DISTRIBUTION LOGISTICS

Parameter	Abbreviation	Unit	Value	Notes
Input data truck < 10 tonne				
Load capacity	LC	*tonne*	3	i
Load factor of loaded trips	LF	*%*	35%	i
Loaded kilometre factor	LKF	*%*	70%	i
Utilisation factor	W%	*%*	24.5%	j
Calculations truck transport Nigeria				
Truck transport distance	D	*km*	257	k
Emissions vehicle-kilometre	E_{vkm}(W%)	*g CO2/vkm*	428	l
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	582	m
Results distribution logistics				
Truck transport Nigeria	GWP truck Nigeria	*g CO2-eq/tonne charcoal*	149,608	n
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data container ship like Panamax				
Container unit capacity	CC	*TEU*	4,112	o
Utilisation TEU capacity	UC	*%*	70%	o
Share of loaded container units	SLC	*%*	60%	o
Load per loaded container unit	LLC	*tonne/TEU*	11.5	p
Energy consumption vehicle-kilometre	ECvkm	*MJ/vkm*	4,410	q
Emission factor fuel	EF fuel	*g CO2/MJ*	76.6	r
Calculations maritime shipping Lagos to Rotterdam				
Shipping distance	D	*km*	8,784	s
Emissions vehicle-kilometre	E_{vkm}	*g CO2/vkm*	337,806	t
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	17	u
Results distribution logistics				
Maritime shipping	GWP shipping	*g CO2-eq/tonne charcoal*	149,404	n
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data truck > 20 tonne				
Load capacity	LC	*tonne*	16	i
Load factor of loaded trips	LF	*%*	60%	i
Loaded kilometre factor	LKF	*%*	75%	i
Utilisation factor (W%)	W%	*%*	45.0%	j
Calculations truck transport Netherlands				
Truck transport	D	*km*	50	v
Emissions vehicle-kilometre	E_{vkm}(W%)	*g CO2/vkm*	1,031	l
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	143	m
Results distribution logistics				
Truck transport Netherlands	GWP truck NL	*g CO2-eq/tonne charcoal*	7,161	n

[i] The load capacity, load factor of loaded trips and loaded kilometre factor of the truck is derived from Den Boer et al., (2011) for average cargo from {Table 37}. [j] The utilisation factor is constructed by multiplying the LF with the LKF. [k] It is assumed that the charcoal is produced in Oyo which is located 257 km from the port of Lagos, Apapa. [l] From {Table 8} in Den Boer et al., (2011) the CO_2 emission factor for the vehicle is derived by using: $\boldsymbol{E_{vkm}(W\%)} = \boldsymbol{E_{vkm}(empty)} + \boldsymbol{W\%} \ast \left(\boldsymbol{E_{vkm}(full)} - \boldsymbol{E_{vkm}(empty)}\right)$. [m] The emissions per tonne-kilometre are afterwards calculated: $\boldsymbol{E_{tkm}} = \boldsymbol{E_{vkm}(W\%)/(LC \ast LF \ast LKF)}$**.** [n] To determine the GWP the E_{tkm} is multiplied with the distance. [o] The load parameters (container capacity, utilisation capacity and share of loaded container units) for the container ship are assumed from Den Boer et al. (2011) from {Table 39}. [p] The Load per loaded container is assumed from Jamala et al. (2013). Around 23 tonnes fill a 40 feet container (2 TEU), therefore is assumed that in a 20 feet container (1 TEU) 11.5 tonnes charcoal is transported. [q] For the energy consumption per vehicle-kilometre the 2009 data from Den Boer et al. (2011) is assumed from {Table 26}. [r] Emission factor is assumed from the 2009 data from Den Boer et al. (2011) derived from {Table 29}. [s] The shipping distance from the port of Lagos, Apapa (Nigeria) to the port of Rotterdam (the Netherlands) is 4743 nautical miles (Ports, 2017), resulting in 8784 km. [t] The CO_2 emissions per vehicle-kilometre are than calculated by multiplying the ECvkm with EFfuel. [u] The emissions per tonne-kilometre are calculated using: $E_{tkm} = \boldsymbol{E_{vkm}/(CC \ast UC \ast SLC \ast LLC)}$**.** [v] The distribution distance in the Netherlands is assumed to be 50 km based on JRC (2017).

Table 26. End-use *Scenario NG*.

END-USE				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data charcoal combustion				
Emission factor CO2	EF_{CO2}	*kg CO2/TJ charcoal*	112,000	w
Emission factor CH4	EF_{CH4}	*kg CH4/TJ charcoal*	200	w
Emission factor N2O	EF_{N2O}	*kg N2O/TJ charcoal*	1	w
Calculations combustion				
Emissions CO2	E_{CO2}	*g CO2/MJ charcoal*	112	x
Emissions CH4	E_{CH4}	*g CH4/MJ charcoal*	0.20	x
Emissions N2O	E_{N2O}	*g N2O/MJ charcoal*	0.001	x
Results end-use				
Combustion	GWP combustion	*g CO2-eq/MJ charcoal*	118	y

[w] The default emission factors for residential charcoal combustion based on the LHV are considered from *Chapter 2: Stationary Combustion* of Gómez et al. (2006) {Table 2.5 (continued)}. [x] The emission factors in [kg pollutant/MJ charcoal combusted] is calculated towards the unit [g pollutant/MJ charcoal combusted]. [y] The GWP for combustion in the end-use stage is calculated using equation 1, as the biomass is harvested unsustainable, the biogenic CO_2 released is included within this calculation.

Appendix C: GWP data for *Scenario EU*

Table 27. Feedstock logistics *Scenario EU.*

FEEDSTOCK LOGISTICS				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Calculations harvesting/bundling				
Emissions CO2	E_{CO2}	*g CO2/tonne bundle*	27,527	z
Emissions CH4	E_{CH4}	*g CH4/tonne bundle*	34	z
Results biomass production and feedstock logistics				
Harvesting/bundling	GWP harvesting	g CO2-eq/tonne bundle	28,484	aa
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Calculations forwarding				
Emissions CO2	E_{CO2}	*g CO2/tonne bundle*	2648	z
Emissions CH4	E_{CH4}	*g CH4/tonne bundle*	2.25	z
Results feedstock logistics				
Forwarding	GWP forwarding	g CO2-eq/tonne bundle	2711	aa
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input intermediate transport				
Emission factor CO2	EF_{CO2}	*g CO2-eq/MWh/100 km*	5,600	ab
Calculations intermediate transport				
Truck transport distance	D	km	100	ab
Emissions CO2	E_{CO2}	*g CO2-eq/tonne bundle*	23,520	ac
Results feedstock logistics				
Hauling	GWP hauling	g CO2-eq/tonne bundle	23,520	ad
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Calculations sizing				
Emissions CO2	E_{CO2}	*g CO2/tonne bundle*	823	z
Emissions CH4	E_{CH4}	*g CH4/tonne bundle*	267	z
Results feedstock logistics				
Sizing	GWP sizing	*g CO2-eq/tonne*	2,711	aa

[z] The emissions for the biomass production and feedstock logistics is derived from SimaPro and given in mass bundles for dry energy wood from plantations. Silviculture is considered within these values, but included within the emissions of harvesting/bundling and not given separately [aa] The GWP for biomass production and feedstock logistics is calculated using equation 1. [ab] The data for intermediate transport for energy wood bundles, also referred to as hauling, is derived from Eriksson (2008), giving the GHG emissions already in CO2-eq per MWh. In this article, a bundle is 2.1 MWh/tonne (wet wood 50% moisture content wet basis) for 100 km. [ac] The emissions related hauling for wet wood are now calculated to bundle dry wood. [ad] The GWP for hauling is calculated using equation 1.

Table 28. Conversion *Scenario EU*.

CONVERSION				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data industrial kiln				
Emission factor CO2	EF_{CO2}	*g CO2/kg dry biomass*	404	ae
Emission factor CH4	EF_{CH4}	*g CH2/kg dry biomass*	0.0037	ae
Emission factor CO2, fossil	$EF_{CO2,fossil}$	*g CO2/kg dry biomass*	29,7	af
Calculations carbonisation				
Emissions CO2	E_{CO2}	*g CO2/tonne dry biomass*	404,000	ag

Emissions CH4	E_{CH4}	*g CH4/tonne dry biomass*	3.7	ag
Emissions CO2, fossil	$E_{CO2,\ fossil}$	*g CO2/tonne dry biomass*	29,700	ag
Results conversion				
Conversion	GWP conversion	*g CO2-eq/tonne charcoal*	90,314	ah

[ae] The emission factors for charcoal production originate from Steng (n.d.) {Table 3.1} scenario. [af] It is assumed that besides internally used syngas, also fossil fuels are needed to heat the pyrolysis process. This is assumed from Kung et al. (2013). [ag] The emission factors are converted from [g EF/kg tonne dry biomass] to emissions [g E/tonne dry biomass]. [ah] The GWP for conversion is calculated using equation 1, as the biomass is harvested sustainable, the biogenic CO_2 released is excluded within this calculation. However, the contributing fossil fuels are included.

Table 29. Distribution logistics *Scenario EU*.

DISTRIBUTION LOGISTICS [DL]				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data truck > 20 tonne				
Load capacity	LC	*tonne*	16	i
Load factor of loaded trips	LF	*%*	60%	i
Loaded kilometre factor	LKF	*%*	75%	i
UF (W%)	W%	*%*	45.0%	j
Calculations truck transport Finland				
Truck transport distance	D	*km*	100	ai
Emissions vehicle-kilometre	E_{vkm}(W%)	*g CO2/vkm*	1,031	l
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	143	m
Results distribution logistics				
Truck transport Finland	GWP truck F	*g CO2-eq/tonne*	14,321	aj
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data container ship like Handymax				
Container unit capacity	CC	*TEU*	2,400	o
Utilisation TEU capacity	UC	*%*	70%	o
Share of loaded container units	SLC	*%*	60%	o
Load per loaded container unit	LLC	*tonne/TEU*	11.5	p
Energy consumption vehicle-kilometre	ECvkm	*MJ/vkm*	3,404	q
Emission factor fuel	EF fuel	*g CO2/MJ*	76.6	r
Calculations maritime shipping Finland to Rotterdam				
Shipping distance	D	*km*	2598	ak
Emissions vehicle-kilometre	E_{vkm}	*g CO2/vkm*	260,746	t
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	22.49	u
Results distribution logistics				
Maritime shipping	GWP shipping	*g CO2-eq/tonne*	58,447	aj
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data truck > 20 tonne				
Load capacity	LC	*tonne*	16	i
Load factor of loaded trips	LF	*%*	60%	i
Loaded kilometre factor	LKF	*%*	75%	i
UF (W%)	W%	*%*	45.0%	j
Calculations truck transport Netherlands				
Truck transport	D	*km*	50	v

Emissions vehicle-kilometre	E_{vkm}(W%)	*g CO2/vkm*	1,031	l
Emissions tonne-kilometre	E_{tkm}	*g CO2/tkm*	143	m
Results distribution logistics				
Truck transport Netherlands	GWP truck NL	*g CO2-eq/tonne*	7,161	aj

[ai] The transport distance from the industrial kiln to the port of Helsinki is assumed to be 100 km. [aj] The GWP for distribution logistics is calculated using equation 1. [ak] The shipping distance from the port of Helsinki (Finland) to the port of Rotterdam (the Netherlands) is 1403 nautical miles (Ports, 2017), resulting in 2598 km.

Table 30. End-use *Scenario EU*.

END-USE				
Parameter	**Abbreviation**	**Unit**	**Value**	**Notes**
Input data charcoal combustion				
Emission factor CO2	EF_{CO2}	*kg CO2/TJ charcoal*	112000	w
Emission factor CH4	EF_{CH4}	*kg CH4/TJ charcoal*	200	w
Emission factor N2O	EF_{N2O}	*kg N2O/TJ charcoal*	1	w
Calculations combustion				
Emissions CO2	E_{CO2}	*g CO2/MJ charcoal*	112	x
Emissions CH4	E_{CH4}	*g CH4/MJ charcoal*	0.2	x
Emissions N2O	E_{N2O}	*g N2O/MJ charcoal*	0.001	x
Results end-use				
Combustion	GWP combustion	*g CO2-eq/MJ charcoal*	5.87	al

[al] The GWP for combustion in the end-use stage is calculated using equation 1, as the biomass is harvested sustainable, the biogenic CO_2 released is excluded within this calculation.

Appendix D: Inflation rates

Table 31. Inflation rates in Europe, Nigeria and the USA for the period 1995 – 2016.

Parameter	**Value**		
	Europe	*Nigeria*	*USA*
1995			2.81%
1996			2.93%
1997	1.57%	8.53%	2.34%
1998	1.10%	10.00%	1.55%
1999	1.10%	6.62%	2.19%
2000	2.10%	6.93%	3.38%
2001	2.35%	18.87%	2.83%
2002	2.24%	12.88%	1.59%
2003	2.09%	14.03%	2.27%
2004	2.14%	15.00%	2.68%
2005	2.18%	17.86%	3.39%
2006	2.18%	8.24%	3.23%
2007	2.13%	5.38%	2.85%
2008	3.28%	11.58%	3.84%
2009	0.29%	11.54%	-0.36%
2010	1.62%	13.72%	1.64%
2011	2.71%	10.84%	3.16%
2012	2.50%	12.22%	2.07%
2013	1.35%	8.48%	1.46%
2014	0.43%	8.06%	1.62%
2015	0.03%	9.02%	0.12%
2016	0.24%	15.70%	1.26%

Appendix E: Original data from trade databases

EU's charcoal import in quantity from Nigeria

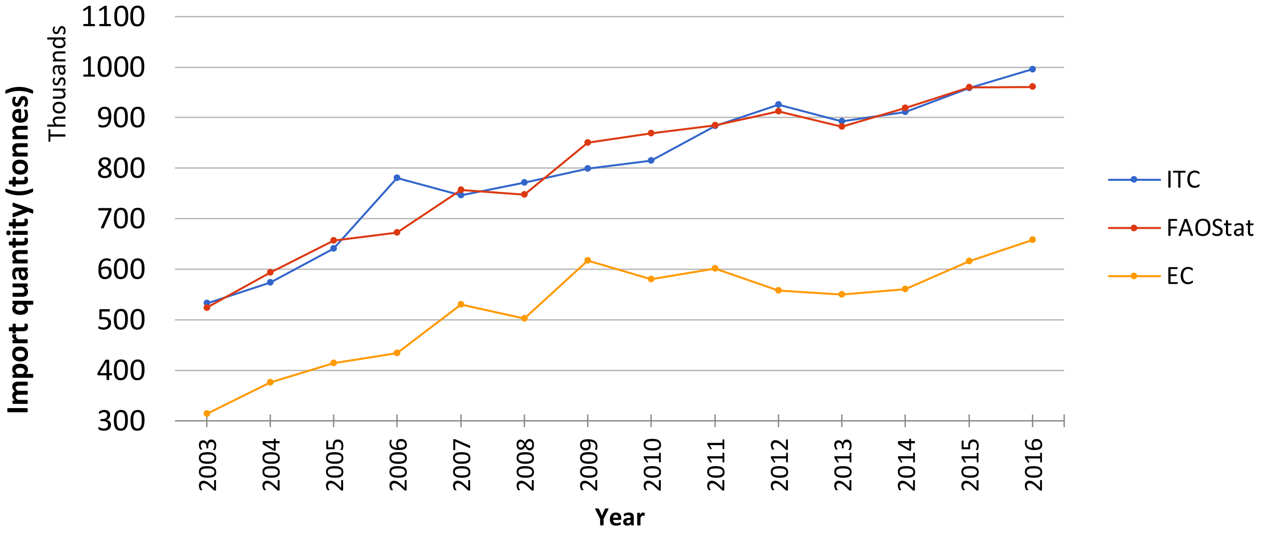

Figure 26. EU's charcoal import in quantity from the world over the period 2003 – 2016.

In Figure 26, the original data from the three databases is presented for the EU's charcoal import in quantity from Nigeria. The data from the FAO and ITC databases are quite similar; however, there is a large difference with the data from the EC database. As explained in the "Methodology", this difference is because the EC database excludes intra-EU trade in the total EU's imports, this means it only considers the extra-EU trade between the EU and non-EU countries and does not take trade between EU member states into account.[22] According to the ITC and FAO database, an average of 978 ktonnes charcoal was imported by the EU, including intra-EU trade. However, according to the EC database, a total of about 658 ktonnes was imported by the EU, representing the extra-EU trade.

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[22] This is checked by combining the intra-EU import in monetary values from the ITC database with the data from the EC database, resulting in a purple line named control (Figure 29).

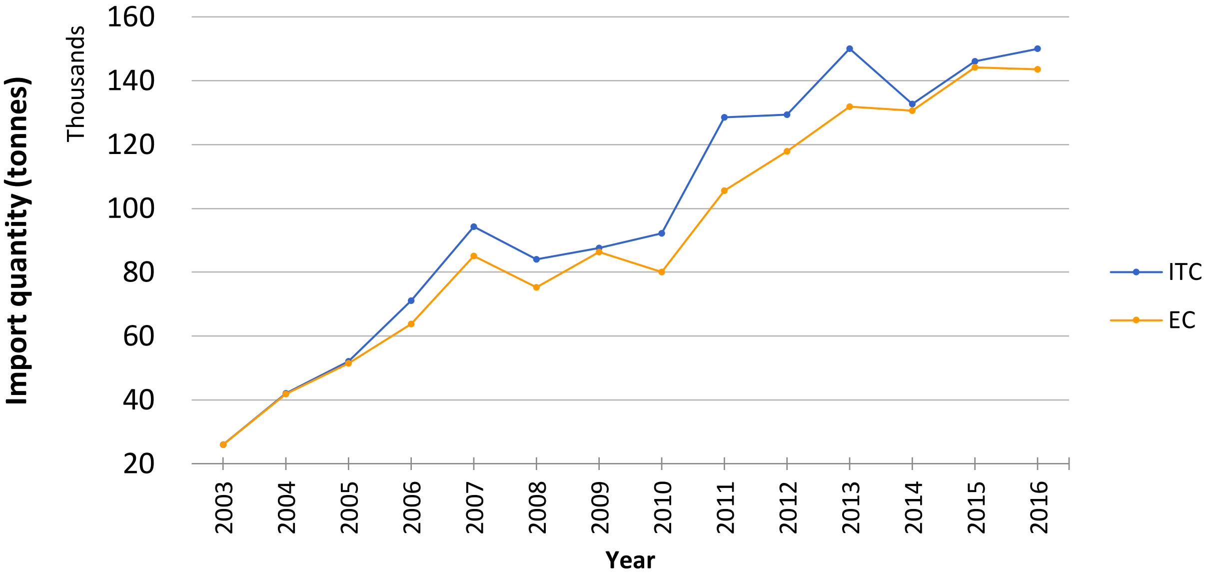

Figure 27. EU's charcoal import in quantity from Nigeria over the period 2003 – 2016.

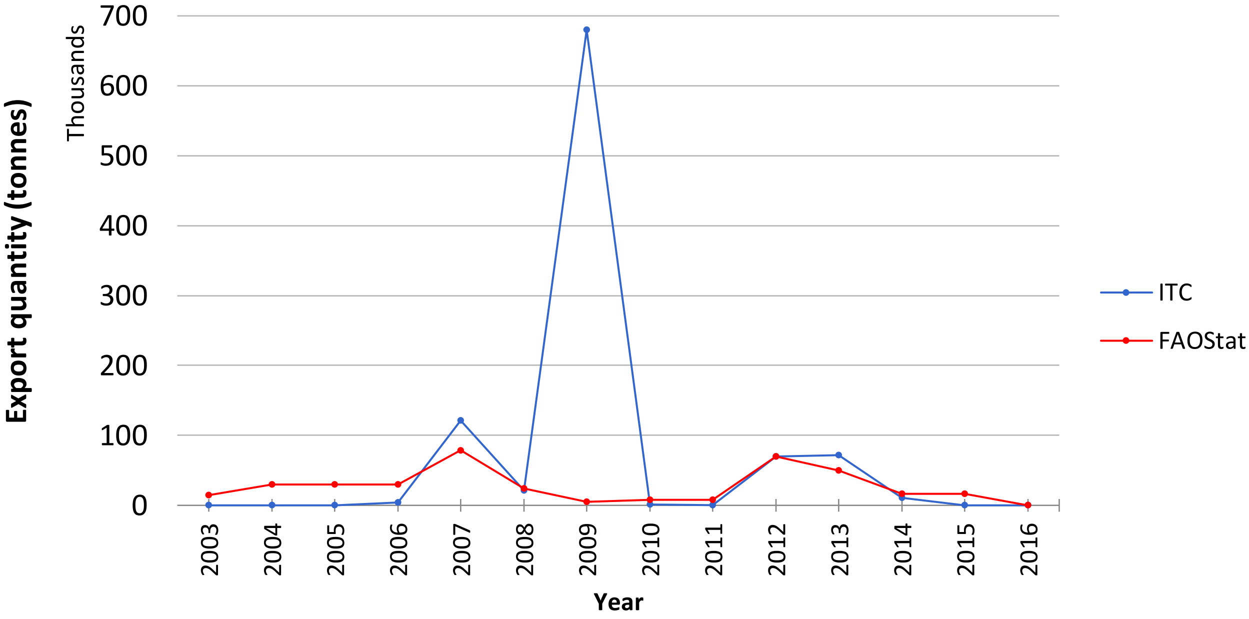

Figure 28. Nigerian export in quantity to the world over the period 2003 – 2016.

EU's charcoal import in monetary value from the world and Nigeria

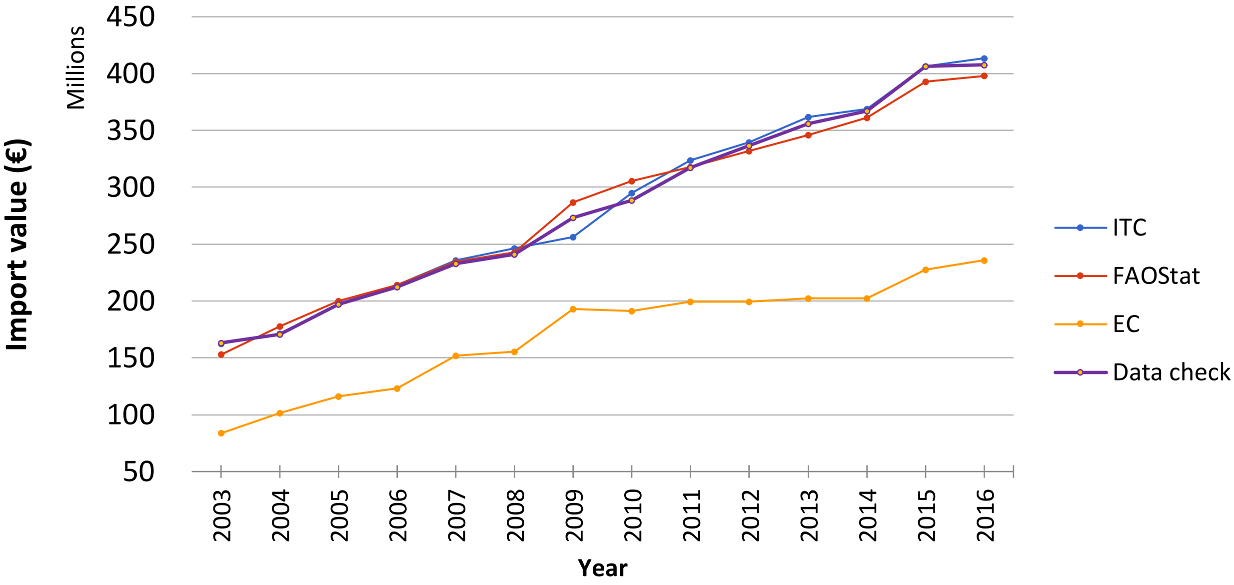

Figure 29. EU's global charcoal import in monetary value over the period 2003 – 2016.

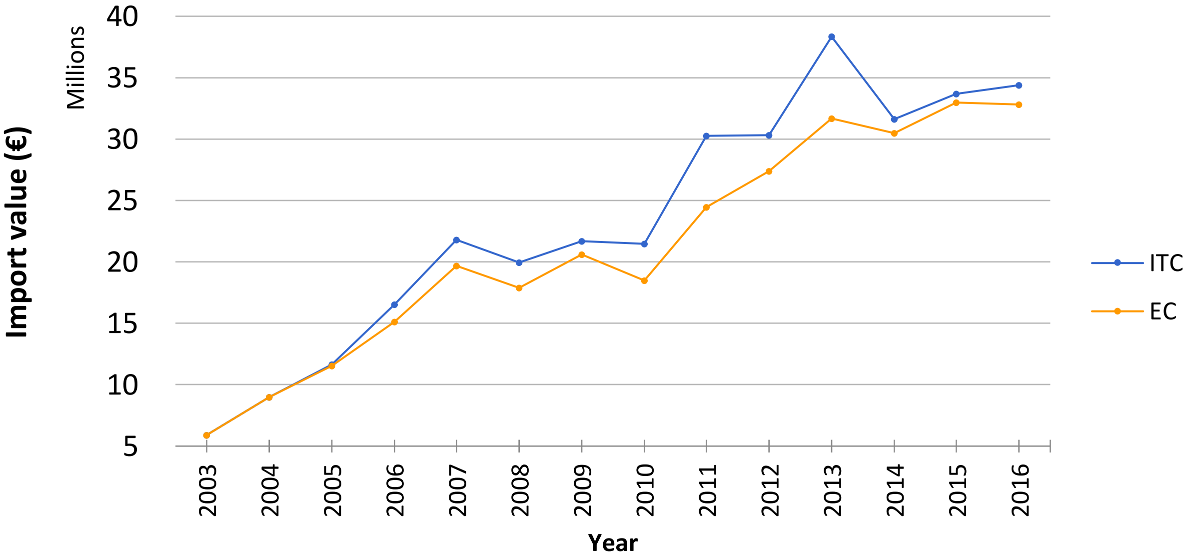

Figure 30. EU's Nigerian charcoal import in monetary value over the period 2003 – 2016.

EU's import prices for global and Nigerian charcoal

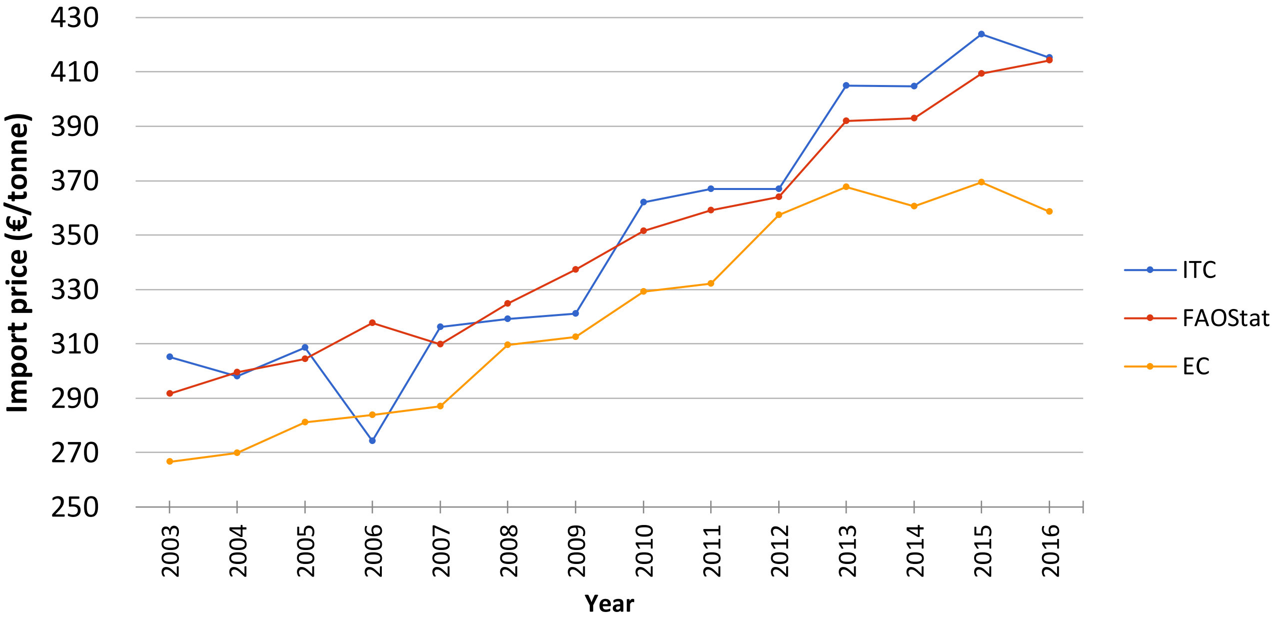

Figure 31. EU's import price for global charcoal over the period 2003 – 2016.

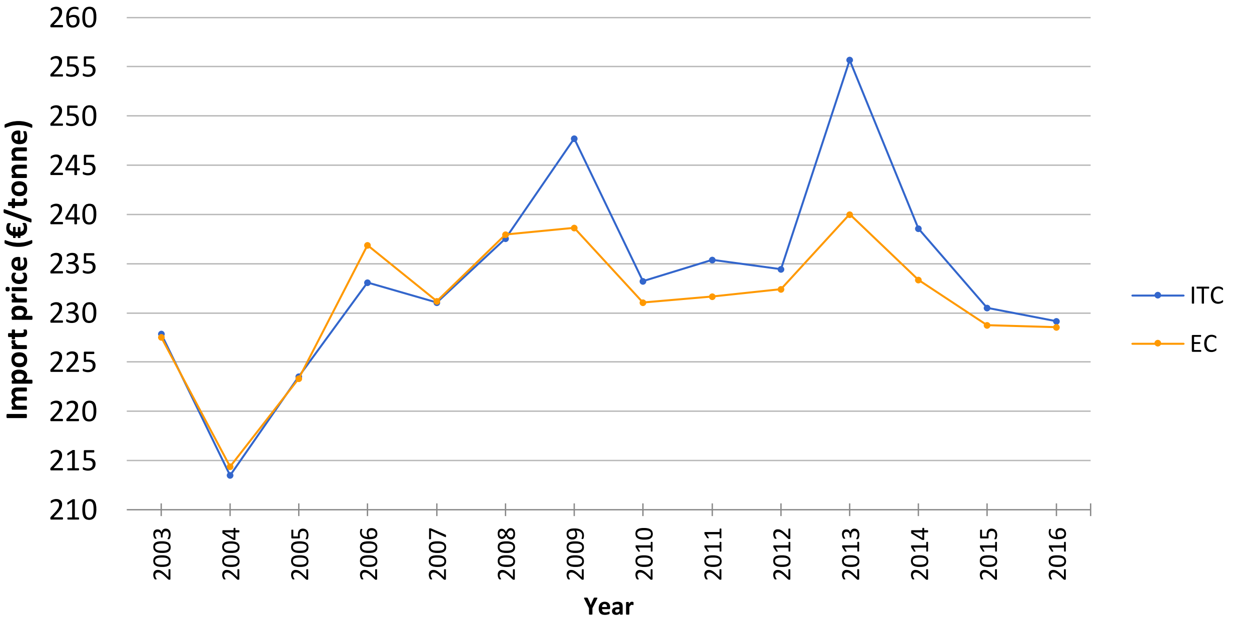

Figure 32. EU's import price for Nigerian charcoal over the period 2003 – 2016.

EU's import from top suppliers

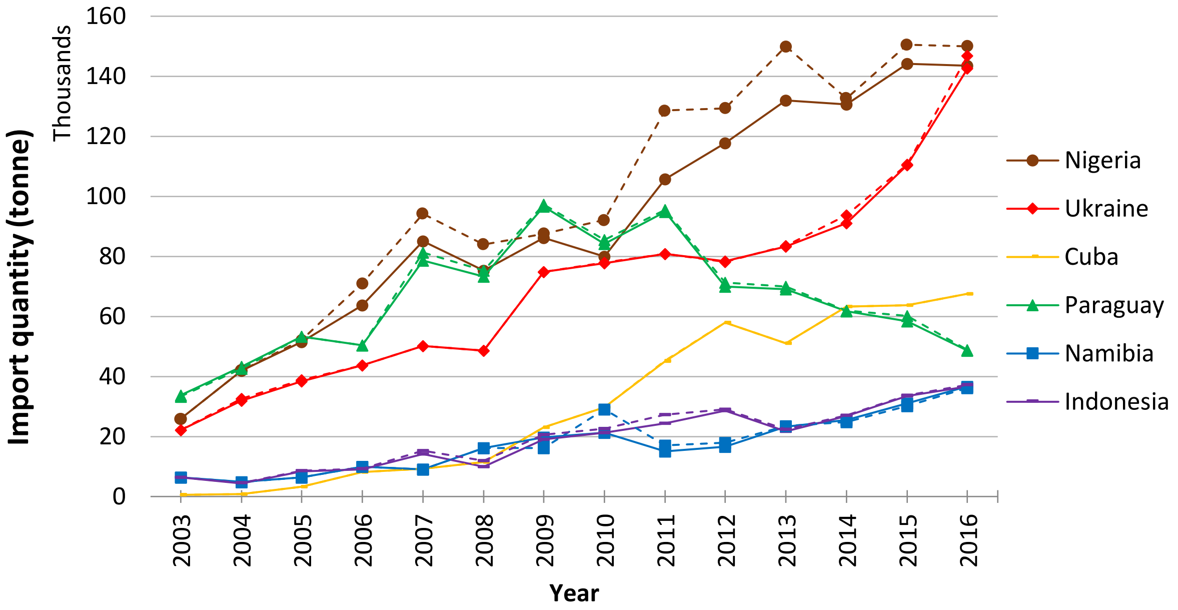

Figure 33. EU's charcoal import in quantity from the six top suppliers, the straight lines are from the EC database, the dotted lines from the ITC database.

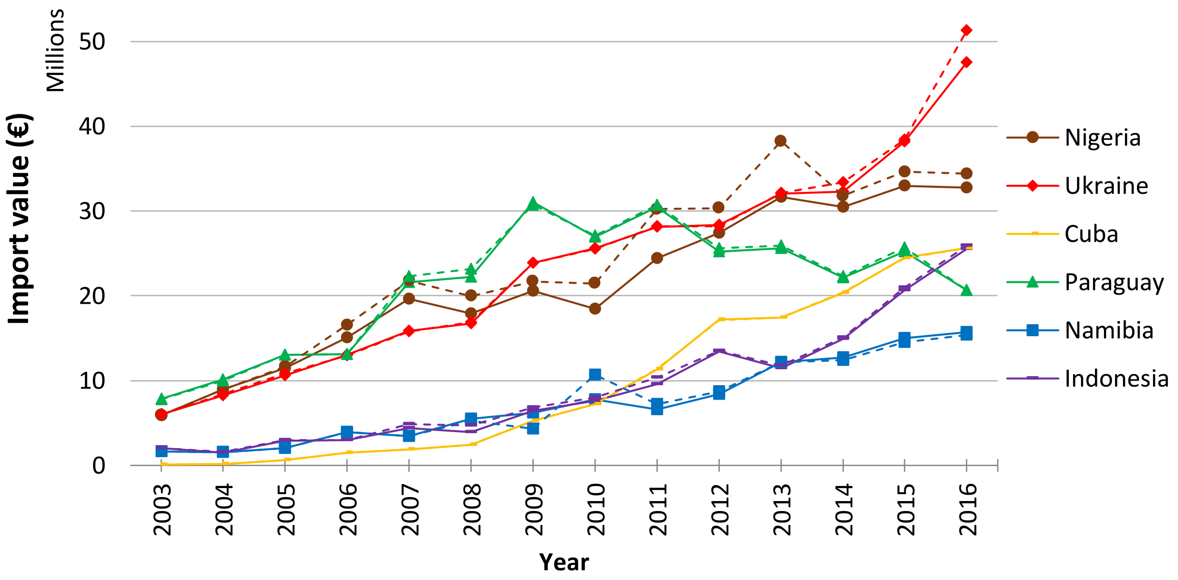

Figure 34. EU's charcoal import in monetary value from the six top suppliers, the straight lines are from the EC database, the dotted lines from the ITC database.

Appendix F: Cost structure Nigerian charcoal

This section explains in more detail how the costs of Nigerian charcoal is accumulated, visible in Figure 35.

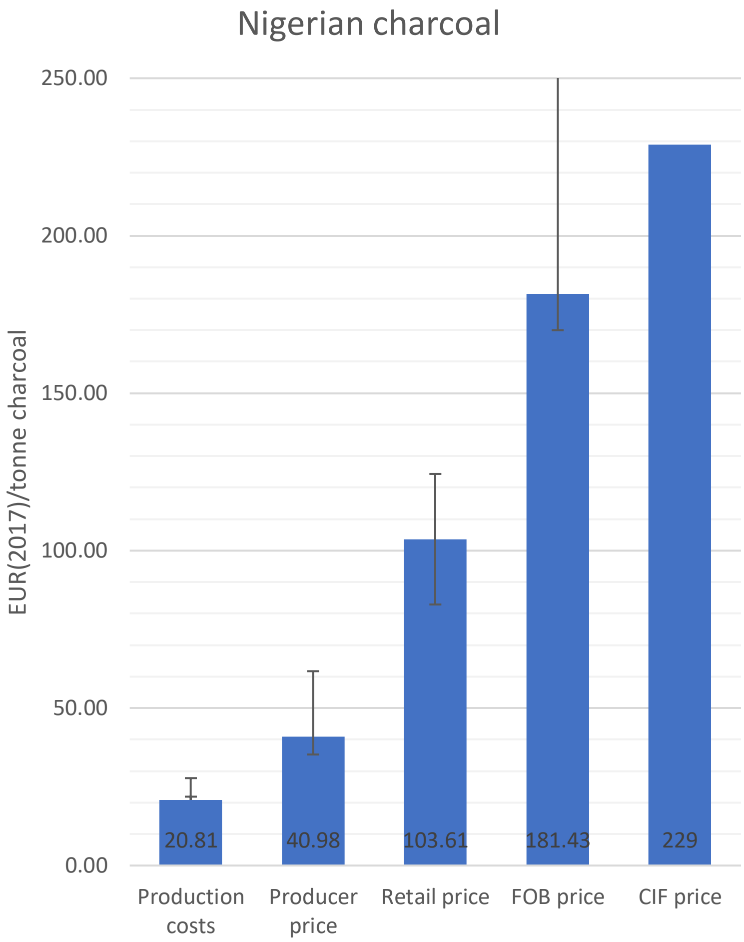

Figure 35. Cost structure Nigerian charcoal.

In Nigeria, production costs are around 20.81 €/tonne (Aiyeloja & Chima, 2011). This extremely low price is caused by two main reasons. First, due to the fact that the charcoal producers typically do not pay for their feedstock (Fadare, 2017). Secondly, the investment costs of traditional kilns are extremely low, because the earth pit and earth mound kiln almost have no investment costs. The only tools that are needed and bought are a chainsaw, axe, machete, hoe, shovel and fork (Luoga et al., 2000). The production costs are quite similar to general data from FAO (2017), the associated costs of an earth-pit kiln were approximately 24.84 €/tonne charcoal[23].

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[23] Assuming the kiln operates for one year. It is unknown how many times the kiln is used.

The selling price of charcoal for a farmer in Nigeria is around 40.98 €/tonne (Aiyeloja & Chima, 2011). This price is similar to the 39.37 €/tonne published by Novus Agro (2016), however, a higher farm price of 52.80 €/tonne was recently published by the newspaper (Fadare, 2017). A reason for this difference is not found.

Afterwards, retailers sell the charcoal for 103.61 €/tonne (Novus Agro, 2016), where except from transportation costs no additional costs were added by the retailers. An article with somewhat older data published that the charcoal retail price in SSA in 2003 was stable over the past years, resulting in 113.42 €/tonne (Zulu & Richardson, 2013).

The free on board (FOB) price for charcoal in Nigeria is around 181.43 €/tonne (Daramola & Ayeni, 2016). A forum, called Nairaland, presents a somewhat higher FOB price and distinguishes bulk charcoal and packed charcoal, 193.40 and 236.38 €/tonne, respectively. Jamala et al. (2013) illustrates a somewhat lower price, European charcoal buyers pay 173.50 €/tonne for charcoal.