Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Energy and Technology

Wood pellet as an alternative cooking fuel in Mozambique
– emission performance of a wood gasification stove

Pellet de madeira como um combustível alternativo para cozinhar em Moçambique
– desempenho de emissões de um fogão gaseificador de madeira

Jessica Vesterberg

Bachelor of Science with a major in Environmental Science

Institutionen för energi och teknik
Department of Energy and Technology

Examensarbete 2014:12
ISSN 1654-9392
Uppsala 2014

SLU, Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Energy and Technology
Institutionen för energi och teknik

Swedish title: Träpellets som ett alternativt bränsle vid matlagning i Mozambique - utsläpp från en småskalig vedspis med förgasningsteknik

English title: Wood pellet as an alternative cooking fuel in Mozambique - emission performance of a wood gasification stove

Portuguese title: Pellet de madeira como um combustível alternativo para cozinhar em Moçambique – desempenho de emissões de um fogão gaseificador de madeira

Author: Jessica Vesterberg

Main supervisor: Gunnar Larsson, Department of Energy and Technology, SLU
Co-supervisors: Johan Vinterbäck, Department of Energy and Technology, SLU
Almeida Sitoe, Faculty of Agronomy and Forestry Engineering, EMU
Examiner: Cecilia Sundberg, Department of Energy and Technology, SLU
Credits: 15 hp
Level: Bachelor
Name of course: Independent project in Environmental Science - bachelor project
Course code: EX0688
Programme/education: Bachelor of Science with a major in Environmental Science
Title of series, no: Examensarbete (Institutionen för energi och teknik, SLU), 2014:12
ISSN: 1654-9392
Cover: Introduction of the wood gasification stove among households in Matola Rio, Mozambique. Photo: Shanar Tabrizi, 2013.

Uppsala 2014

Keywords: Cooking fuel, wood pellets, wood gasification stove, emissions, carbon monoxide, particulate matter, MFS

Online publication: http://stud.epsilon.slu.se

ABSTRACT

The majority of the households in Mozambique rely on solid biomasses, such as charcoal and firewood, for their cooking practices. Combustion of solid biomass is a significant source of particulate and carbon monoxide (CO) emissions. Not only has the increasing demand of charcoal and firewood lead to an escalation of deforestation, but also the emissions from the combustion of the fuels are highly correlated to harmful health effects. Mozambique has vast natural recourses, especially forestland. The established wood processing industry in the country produces large amounts of by-products that could be compressed to the dense and high calorific fuel, wood pellets. This study compares the particulate and carbon monoxide emissions generated from wood pellets, birch firewood and torrefied bamboo pellets, when combusted in wood gasification stoves (WGS). Furthermore interviews were conducted with households and wood industry companies to investigate the possibility of introducing wood pellets in combination with WGS. The preferred fuel among the households was the torrefied bamboo pellet because of its smooth burning characteristic. Wood pellets had high flames, easily burning food. The laboratory tests showed that wood pellets had the lowest emissions of both CO and particulate matter (PM). Using torrefied bamboo pellets in the WGS would violate the WHO guidelines for human exposure of CO, 114 ppm for more than 15 minutes. The stove was adjusted in order to lower the CO and PM emissions, but the results from laboratory tests did not show any substantial differences. However, considering user friendliness, rotating three of nine bottom tiles in order to decrease the primary airflow in combination with expanding the upper tiles from 4.2 mm to 5.0 mm lowered fuel consumption, less soot was seen on the pot and the flame was easily regulated.

Keywords: Cooking fuel, wood pellets, wood gasification stove, emissions, carbon monoxide, particulate matter, MFS

RESUMO

A maioria das residências em Moçambique dependem de biomassas sólidas, como carvão e lenha, para cozinhar. Combustão de biomassa sólida é uma fonte significante de partículas e de emissão de monóxido de carbono (CO). Não só o aumento na demanda de carvão e lenha tem levado a uma escalação no desflorestamento, mas também a emissão da combustão dos combustíveis estão altamente correlacionadas a efeitos de doenças perigosas. Moçambique tem vastos recursos naturais, especialmente na área de florestamento. A indústria de processamento de madeira estabilizada no país produz grandes quantidades de subprodutos que poderia ser comprimidos para o denso e altamente calorífico combustível, pellets de madeira. Este estudo comparam as partículas e emissões de monóxido de carbono que são gerado pelo pellet de madeira, lenha de bétula e bambu torrado, quando queimado em fogão gaseificador de madeira (WGS). Além disso, entrevistas foram conduzidas com residências e companhias de indústrias de madeira para investigar a possibilidade de introduzir pellets de madeira em combinação com fogão gaseificador de madeira. O combustível preferido entre as residências foram os pellets de bambu torrado, pela característica de queima lenta. Pellets de madeira tinham chamas altas, queimando facilmente a comida. Os testes de laboratórios mostraram que pellets de madeira teve os emissões mais baixo tanto no monóxido de carbono como no material particulado (PM). Usar pellets de bambu torrado no fogão gaseificador de madeira violaria as orientações da WHO para exposição humana de CO, 114ppm por mais de 15 minutos. O fogão foi ajustado afim de reduzir as emissões de CO e PM, mas os resultados de laboratórios não mostraram diferenças substanciais. No entanto, considerando a facilidade de utilização, em rotação de três de nove azulejos de fundo, a fim de diminuir o fluxo de ar primário em combinação com a expansão das telhas superior de 4,2 mm a 5,0 milímetros reduzido o consumo de combustível, menos fuligem foi visto na panela e a chama foi facilmente regulada.

Palavras-chave: combustível para cozinhar, pellets de madeira, fogão gaseificador de madeira, emissões, monóxido de carbono, material particulado, MFS

ACKNOWLEDGEMENT/PREFACE

This report is a result of two months of field works in Mozambique. The study was conducted with Shanar Tabrizi, a technology student at Uppsala University. She studied the technical aspects of the Philips wood gasification stove in combination with several fuels, e.g. fuel consumption and efficiency. Those results are accessible in the report Wood Pellets in Mozambique – An alternative to charcoal and firewood for cooking in Mozambican households (Tabrizi, 2014). My main focus was the emissions performance of the stove, as presented in this report.

This project could not have been possible without the kind assistance of some people to whom I would like to express my gratitude.

First of all, I would like to thank the Swedish International Development cooperation Agency, Sida, for the economical support throughout this study. I owe deep gratitude to my Swedish supervisor, Gunnar Larsson, for helping me with the academic parts of this study; also to Johan Vinterbäck who introduced this project to me.

A special thank to my Mocambican supervisor Almeida Sitoe who helped with many of the practical parts; also to Rosta Mate, Percinio, Julieta, Ivone, Miguel and Niolau at Eduardo Mondlane University (EMU) who helped at the institute and in field.

I am grateful to have shared an unforgettable journey with Shanar Tabrizi, my friend and colleague through this project. I am deeply endebted to all the households in which I worked, in particular the women of Matola Rio who made this study possible. I thank them for their hospitality and warmth, for being patient throughout the many interviews and also for testing the fuels. It was a a pleasure getting to know and working with all of them.

Last, but definitely not least; I sincerely thank you my sister, mother and Simon Haile for all the moral support throughout.

15 April of 2014, Uppsala

ACRONYMS

CO – Carbon monoxide

EMU – Eduardo Mondlane University

MZN – Mozambican metical

PM – Particulate matter

Sida – Swedish International Development cooperation Agency

SLU – Swedish University of Agricultural Sciences

USD – United States dollar

UTC – Coordinated universal time

WGS – Wood gasification stove

WBT – Water boiling test

Mid market rate: 1.0 MZN = 0.032 USD (2014-04-05 13.47 UTC)

TABLE OF CONTENTS

1. INTRODUCTION

Mozambique is located in the eastern part of Southern Africa and compromises a land surface of 800 000 km^2, with a population of nearly 24 million inhabitants (UN, 2013b). The country gained independence from Portuguese colonial rule in 1975, soon to be followed by a protracted and destructive civil war that was ended in 1992. In 1994 Mozambique had its first democratic election that led to a political stability and to one of the world's most rapid examples of economic growth, averaging approximately 7.5% annually (Mulder and Tembe, 2008). Nevertheless it is still one of the world's poorest countries with a Gross Domestic Product (GDP) per capita of US$536 and a Human Development Index rank of 185 out of 187 countries (UN, 2013b). Mozambique is highly dependent on foreign aid, which currently encompasses roughly half of the government budget (UNDP, 2013).

Mozambique has vast natural resourses, including hydro potential, natural gas reserves and proven coal reserves (Mulder and Tembe, 2008). Last but not least are the country's vast forestry assets; forestland accounts for 50% of the country's total land area (UN, 2013b). Biofuels are not only environmental beneficial, but also 'a pathway out of poverty' for developing countries. Biofuels can provide incentives in agricultural and forestry research and development, and also stimulate linkages to input and food markets that presently do not exist. Like many other countries Mozambique has discovered the advantages of biofuels (Schut et al., 2010).

Nevertheless, no more than 18% of the households in Mozambique have access to electricity, which leaves the majority of the population, 90%, depending on traditional energy sources such as charcoal and firewood for domestic use (Mahumane et al., 2012). This has lead to an increasing deforestation rate of 0.53% annually, equating to approximately 200,000 ha/year (FAO, 2010). The increasing use of traditional cooking fuels is not only hazardous to forestation, biodiversity and soils, but also to human health. Gaseous and particulate emissions cause harmful health effects for users of cooking stoves and to local residents (Ezzati et al., 2002). Furthermore, the earth's radiation balance is affected both directly and indirectly by cloud interactions from PM emissions. Combustion of biofuel is a significant source of PM, producing approximately 20% of global emissions of both organic carbon and elemental carbon (Bond et al., 2004). Nearly 1.6 million premature deaths and approximately 3% of the global burden of disease are caused by exposure to indoor air pollutants associated with household solid fuel (WHO, 2006).

An alternative to traditional fuels for cooking could be wood pellets. Wood pellets are a compressed by-product of the forest products industry, usually being compressed wood chips and sawdust. Its characteristics are a uniform size, low moisture content and high calorific value. Mozambique has theoretically large volumes of residuals and raw material that could be used to produce wood pellets. The country has over 120 functional sawmills producing massive volumes of sawdust (Nhancale et al., 2009). The furniture industry is largely adopted in the country, especially in or in connection to the big cities. By-products from furniture industry are dried as a result of the manufacturing process, and therefore they do not require as much energy consuming drying as sawdust from sawmills. A great palm plantation in the central province of Zambezia was recently infected by bacteria, transmitted by a planthopper bug (haplaxius crudus). The bacteria caused the foliage of an infected palm tree to turn yellow and then brown, killing the tree within six months. The plantation in Zambezia was once the world's largest, but the disease has killed over 7 million palm trees, which could be used as raw material for pellet production. All these sources of residuals and raw material have potential to produce pellets economically, and potentially at competitive levels to charcoal in larger cities.

Pellet production in Mozambique is currently non-existent, although neighbouring South Africa has a few pellet producers and Zambia has a couple of start-up companies. Pellets cannot be burned in the currently recognized stoves in Mozambique, because of the low airflow they offer. Paul van der Sluis, principal research scientist at Philips Research Laboratories in the Netherlands, has designed a wood gasification stove intended to burn wood, animal dung or other biomass both more efficiently and cleaner than traditional stoves (AfricanCleanEnergy, 2014). The technology of the stove can be compared with a pellet boiler; it is only a simplified and smaller version. The stove has therefore proven very able to burn wood pellets, for example in a project in Zambia (CradleToCradle, 2014).

Introducing improved cooking stoves to the citizenry of sub-urban Maputo can be seen as a small push to achieve The United Nations Millennium Development Goal 7; Ensure environmental sustainability (UN, 2013a). Not only are trees saved from being cut down, but also stove users' environmental awareness increases.

2. AIM

The aim of this study is to compare carbon monoxide (CO) and particulate matter (PM) emissions from three types of biofuels burned in a wood gasification stoves (WGS): wood pellets, torrefied bamboo pellets and birch firewood. By interviewing households and wood industries, the feasibility of using wood pellet as an alternative cooking fuel in sub-urban households in Maputo, Mozambique will furthermore be assessed. The object is to minimise the consumption of the traditional cooking fuels, firewood and charcoal by introducing a more sustainable alternative and also to extract other possible benefits from wood pellets.

The stove is optimized for burning firewood, animal dung and other biomass. Since this study aims to view the potential of using wood pellets as fuel, the stove will be adjusted for burning wood pellets given particle and CO emissions.

3. FRAME OF REFERENCE

3.1. Domestic energy situation in Mozambique

The extent of the environmental and health issues connected to the usage of charcoal and other biofuels for cooking has only recently begun to receive the attention of researchers and policymakers worldwide (WHO, 2006). The Mozambican government approved in 2009 the National Biofuel Policy and Strategy, an important instrument for the launch of biofuel activity in the country. The strategy is a regulatory framework for production of biofuels by both private and public sectors, based on principles of transparency, energy security, and social and environmental protection (Atanassov et al., 2012).

The "energy ladder" is made up of several rungs, with traditional fuels such as firewood and animal dung occupying the lowest rung. Charcoal, coal, kerosene, gas and electricity, in the given order, represents the next steps of the ladder. As the income per capita increases, households switch more efficient energy systems for their household energy needs, i.e. move up the "energy ladder". The income levels at which people move up the energy ladder has fallen with technological progress (Holdren P. and Smith R., 2000). New technologies, such as the WGS, help the fuels occupying the lowest rung to be used more efficiently and possibly resulting in a cleaner combustion.

Approximately 90 % of the households in Maputo have access to electricity. Nevertheless, 87% of the households use firewood or charcoal for cooking. LPG and electricity are also in relatively common use as cooking fuels. Half of households use these fuels for cooking, but in almost all cases in combination with charcoal and firewood. Firewood is regularly used in a three stone open fire (Figure 1), and charcoal in a stove made of iron (Figure 2), available at most local markets in the urban and sub-urban areas (Atanassov et al., 2012).

Figure 1. A typical set up of a three stone open fire where firewood is used as fuel. A traditional charcoal stove with two openings in the background.

Figure 2. A traditional charcoal stove in Mozambique.

3.2. Deforestation in Mozambique

Atanassov et al (2012) has estimated a daily consumption of charcoal in the Maputo and Matola region to 6700 m^3 of wood. This equates to 390 ha/day of forest to satisfy charcoal demand in these regions, leading to related annual forest clearance of approximately 142,000 ha. The FAO (2010) report shows national deforestation of 200,000 ha annually, indicating that demand for charcoal for cooking is a major contributor to deforestation. Because of the high demand of wood especially near big cities such as Maputo, deforestation around them is significant (Atanassov et al., 2012). The majority of the charcoal, 95-99%, is informally produced and unregulated and leads to a loss in government revenues (Nhancale et al., 2009). The low abundance of forest in these regions affects charcoal prices, leaving the prices around

Maputo much higher than in the northern and central parts of Mozambique (Atanassov et al., 2012).

3.3. Health effects of cooking

Indoor air quality in developing countries is relatively poor. This partly depends on the extent of both indoor and outdoor originated pollution, also arises due to inadequate indoor ventilation. The most significant factor affecting the indoor air quality is combustion of solid fuels for cooking (WHO, 2006). The majority of the households, 70%, in the cities Matola and Maputo cook indoors (Atanassov et al., 2012). This frequently produces very high levels of pollutants, especially CO and PM, which is a major concern for health. Despite this, indoor air pollutants have not been as extensively monitored as outdoors air pollutants, and additional scientific evidence to health effects needs to be assessed (WHO, 2006). Fuel consumption, fuel humidity, combustion conditions such as temperature, airflow and air humidity are all factors that will affect the amount and characteristics of pollutants. All of these characteristics will affect the human body in different ways. Known toxicological characteristics for PM are, among other things, chronic respiratory diseases and for CO reduced oxygen delivery to tissues owing to formation of carboxyhaemoglobin (WHO, 2006). As mentioned above, a risk assessment conducted by the WHO (2006) shows that annually over a million premature deaths are caused worldwide from indoor cooking.

4. LITERATURE STUDIES

4.1. Emissions

4.1.1. Carbon monoxide

Carbon monoxide (CO) is a toxic gas produced from incomplete combustion of carbonaceous fuels such as wood and other biofuels. Incomplete combustion occurs when there is insufficient oxygen to react with the hydrocarbon. The gas is colourless, odourless, non-irritant and tasteless and consequently not detectable by humans. In the human body, CO reacts with haemoglobin in the blood to form carboxy haemoglobin (COHb). Lethal concentrations of CO can occur during combustion of low-grade solid fuels and biofuels in small stoves or fireplaces in non-ventilated spaces (WHO, 2010).

4.1.2. Particulate matter

Such as CO, particulate matter (PM) is often seen as an indicator of incomplete combustion (Johansson et al., 2003).

Different characteristics may be significant to different health effects. Particlate characteristics are complex since airborne particles continue to undergo chemical and physical transformation in the atmosphere. Particles are, despite this, categorised by their aerodynamic properties where the summary indicator is the aerodynamic diameter. The aerodynamic diameter is a hypothetical sphere of a unit-density with the same aerodynamic characteristics as the particle in interest. The U.S. Environmental Protection Agency promulgated a standard for coarse PM with an aerodynamic diameter smaller than 10 µm, PM_{10}, in 1987. Ten years later a standard for fine particulate matter, $PM_{2.5}$, was published. WHO has set guidelines for these PM indicators. Particles smaller than 0.1µm are known as ultrafine particles. No guidelines are set for them. Particles smaller than 2.5 µm are usually generated from combustion processes (WHO, 2006). The main sources of fine particulate matter from small-scale biomass combustion are particles from incomplete combustion, including soot, condensable organic particles (tar) and char (Johansson et al., 2003).

4.2. Indoor air quality guidelines

The WHO has established guidelines to protect against short-term CO peak exposures that might occur from unvented stoves. According to these guidelines a person should not be exposed for a CO concentration higher than 35 mg/m^3, equivalent to 40 ppm, for one hour or 100 mg/m^3, equivalent to 114 ppm, for 15 minutes. These guidelines assume that such exposure does not occur more than once a day (WHO, 2010).

The PM levels are usually higher indoors than outdoors in developing countries because of the usage of solid biofuels in unvented stoves. The households are equipped with poor ventilation, which result in pollution sourced from both indoors and outdoors contributing to indoor pollution. The WHO has therefore concluded that the air quality guidelines for PM recommended by the 2005 global update (WHO, 2006) are applicable to indoor spaces (WHO, 2010). The WHO's air quality guidelines for short term exposures of PM are 50$\mu m/m^3$ for PM_{10} and 25$\mu m/m^3$ for $PM_{2.5}$. Ultrafine particles have recently shown considerable potential of toxic and detrimental effects to human health. The existing body of epidemiological evidence is insufficient to reach a conclusion on the exposure-response relationship to ultrafine particles. No recommendations can therefore be provided as to guideline concentrations of ultrafine particles (WHO, 2006).

4.3. Wood gasification stove

The combustion process in the WGS is simple gasification of biomass, in combination with airflow in two layers.

When the fuel is heated to a temperature above 430 °C, the biomass will releases gas and unburned particulate matter if not enough oxygen is available. This will be seen as smoke. To prevent this, the combustion volume in the stove should reach a higher temperature and the stove should supply the combustion volume with a sufficient oxygen supply.

The Philips WGS has solved this by using a cylindrical stainless steel chamber , embedded with ceramic plates for isolation. It is equipped with an adjustable fan at the bottom to provide the fuel with air, through both primary and secondary airflow, see Figure 3. In the primary combustion zone the fuel partially combusts, resulting in a high temperature which causes the (CO-rich) gas and PM to rise to the secondary combustion zone, where air is forced into the hot gaseous mix. The secondary airflow burns the gaseous mix with almost complete efficacy. This results in high efficiency and lowered release of pollution.

The adjustable fan helps regulate the efficiency and heat of the stove. The stove is equipped with a rechargeable battery to power the fan. When the stove is hot enough, the thermoelectric generator recharges the battery to extend the cooking time between charges. According to the stove instructions, the battery is fully charged after being connected to the electricity grid for 5 hours. It can then be used for cooking for around 21 hours depending upon the frequency with which the stove is lit.

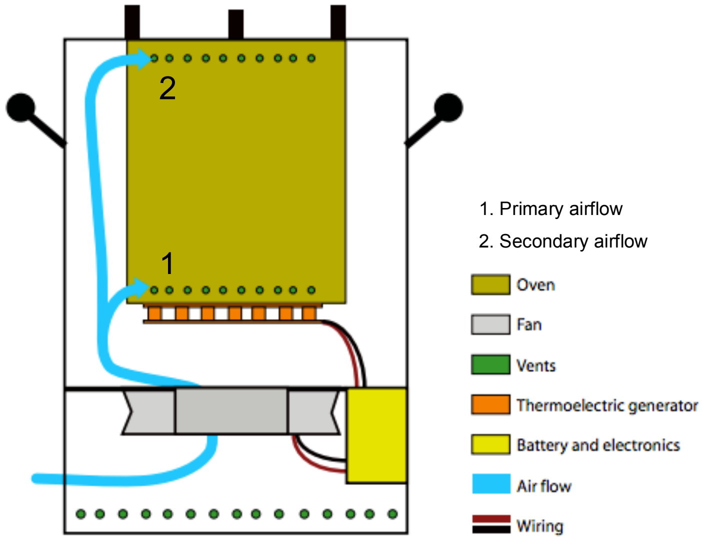

Figure 3. Schematic diagram of the WGS (illustration: Philips, Storm Scott)

5. METHODS

5.1. Interviews

The interviews and household tests were carried out between April and June 2013, pre-winter in Mozambique. Because of the small sample of ten households and two companies in the wood industry, and also to allow a two-way communication, all interviews were conducted using a semi-structured method. A form with topics was prepared in beforehand and used as guidance during the interviews. The majority if the questions were created during the interview, allowing both the interviewer and the person being interviewed flexibility to probe for details (FAO, 2014).

5.1.1. Households

Wood pellets and torrefied bamboo pellets were tested in 10 random households in the sub-urban area of Maputo. The study was carried out in Matola Rio, Kilometro 16, a sub-urban community located approximately 20 km west of Maputo. The requirements for the households to participate in the study was (1) to have access to electricity in order to charge the battery that runs the fan in the stove and (2) to currently use charcoal or firewood for cooking. Demonstration of how to operate the stove, such as how to charge the battery, adjust the fan and how to light it and add fuel was done at the same time as it was distributed. The primary and secondary airflow of the stoves were not modified during the household tests.

An interview was carried out before testing wood pellets with the WGS and a second interview was conducted after testing the fuel in combination with the stove for three to five days. The same households were provided with torrefied bamboo pellets for the same number of days. The object of the first interview was to map current household practices and to reflect on their environmental and health awareness. It also enabled and assessment of their experience or knowledge of improved cooking stoves and alternative cooking fuels. The second interview aimed to record the practical pros and cons of using new fuel in combination with the WGS.

5.1.2. Wood industry

Interviews with companies in the wood industry were conducted the 25th of April and 20th of May. The two participants were *Fersol*, located in the outskirts of Maputo and *Secama* in Matola. Hermina Soares, public relations manager, was interviewed at Secama and Fernando Jorge Souto, company owner, at Fersol.

The objective of the interviews was to assess what kind of residues the wood industry produces and and the method of its disposal in order to investigate their potential for producing wood pellets.

5.2. Emission measurement

5.2.1. The Water Boiling Test

The 2003 revised University of California-Berkeley (UCB) Water Boiling Test (WBT) Version 3.0, 2013, was used to evaluate the wood gasification stove with several types of fuel: wood pellets, birch firewood and torrefied bamboo pellets. The WBT is a laboratory imitation of basic cooking practice that can be performed on most stoves while operating at both high and low power. "While the test is not intended to replace other forms of stove assessment, it is designed to be a simple method by which stoves made in different places and for different cooking applications may be compared by a standardized and replicable protocol" (Bailis et al., 2013). This particular test was chosen because of its recurrence in reports and other writings by international experts in the field.

The WBT consists of three phases: two high power phases (cold start and hot start) and one low power phase (simmering). In the first phase, cold start, the tester begins with the stove, pot and 5 litres of water at room temperature. The water is brought to boil without a lid on. (Bailis et al., 2013) This came to be modified during tests with the torrefied bamboo pellets because of its low power. Lightening paper containing stearin was used to light the fuels.

In the second phase, fresh water at room temperature is boiled by a stove that is already hot. This is to identify differences in performance and emissions between a hot and cold stove. The third phase is a low power test where the tester simmers the remaining water at a temperature approximately 3°C below boiling point for around 45 minutes. The wood mass, the water mass and water temperature are each measured before and between each of these tests. Measuring the stove performance at both high and low power helps to simulate what is likely to occur when cooking foods that involve boiling and simmering. The traditional sub-Saharan main staple food, xima, is cooked in this way and the WBT is therefore a suitable method for evaluating the fuel and stove performance during a cooking session. Xima is made of maize meal, boiled with water to a paste reminiscent of porridge.

The WBT measures both specific fuel consumption and the level of emissions (Tabrizi, 2014). This report focuses on emissions.

All fuels went through three complete WBTs (i.e. nine phases in total) in the wood gasification stove with the same aluminium pot having a diameter of 19.5 cm. The torrefied bamboo pellets were only tested throughout two WBTs (six phases) since the emissions were higher than the maximum capacity of the equipment and had obviously unhealthy effects on the testers. As mentioned above, the WBT with bamboo pellets was performed with a lid to be able to reach boiling point.

The stove was equipped with a fan to regulate the secondary and primary airflow. To keep as many parameters as possible fixed, the fan was set to "medium" during all the phases of the WBT.

5.2.2. Measuring the exhaust

A standardized and commonly employed method for capturing the emissions of cooking stoves is the hood method. In that method, a hood is placed over the stove to capture emissions released during the burn cycle. By capturing the exhaust and measuring the flow rate through the hood, instantaneous changes in burning can be measured. Emissions sampling is conducted between the hood and a fan placed above the hood. The exhaust will cool down and dry simultaneously through natural dilution (Bond and Roden, 2013). This method was not used in this study because of economic and time restraints.

Measurements of emissions were performed in a controlled laboratory setting at the Department of Energy and Technology, SLU, in connection with fuel consumption tests using the WBT. The stove was placed under a fume hood, where a carbon monoxide meter and particular spectrometer were attached, see Figure 4. The sampling procedure was conducted for the entire burning period, since solid fuel emissions are variable both spatially and over time. The sampling procedure recorded over the entire burning period, since emissions from solid-fuel burning are variable in both time and space. This results in a real-time measurement during the complete WBT. Unlike the hood method, this method measures the emissions at a specific location.

Figure 4. Setup in fume hood. Carbon monoxide meter attached to stand and tube leading to an aerosol diluter, which in turn leads to a particular spectrometer.

Carbon monoxide measurement

For measurement of carbon monoxide a carbon monoxide logger, EL-USB-CO Lascar electronics, was used. The CO logger was attached to a stand under the fume hood 75 cm above the stove. The logger contains a sensor that measures the absorbency of infrared radiation every 10 seconds. The concentration of CO in the air is presented both graphically and as a table on the computer, when connected by a USB cable.

Particulate matter sampling

Sampling of PM was conducted using a particular matter meter, Climet CI-500EC, which is a laser diode based aerosol particle counter. The most recent date of calibration was 5th of July 2013. The particle counter can count particles in a 0.3 µm-25 µm interval, divided in six particle channels.

In order to collect the emitted particles, a hose was attached with sellotape on the wall in the fume hood, 85 cm above the stove, as shown in Figure 4. That hose was encrusted with Teflon to minimise the amount of particles attaching to the wall of the hose. Because of the high concentration of PM during combustion of solid fuels, an aerosol diluter was connected between the hose and PM meter. The dilution factor of the aerosol diluter was 1:100. The air sample size of the PM meter during cold start and hot start was set to 0.02 m^3. The sample size was increased to 0.1 m^3 during the simmering test because of the large amount of data it would generate otherwise. The results were printed on thermal paper and manually transcribed to Excel.

The background PM was measured in the fume hood before each WBT. Since the air in the fume hood was constantly exchanged and because of the low values of PM, the background PM was estimated to zero. The airflow was also automatically increased during combustion, which brought the background PM presumably closer to zero.

5.3. Stove adjustment

The initial settings of the WGS are optimized for usage of firewood, animal dung and other biofuels. Therefore, the stove was adjusted in order to minimise the emission of both PM and CO when using wood pellets as fuel.

The stove chamber is embedded with nine lower ceramic tiles and nine upper tiles. Each upper tile has three 4.2 mm holes, which regulate secondary airflow. The lower tiles are equipped with one hole, regulating primary airflow. In order to increase secondary airflow, the middle hole of the top tile, i.e. 9 out of a total of 27 holes, was expanded from 4.2 mm to 5.0 mm. The bottom tiles were rotated 180° to block the air in order regulate primary airflow. Different combinations, presented in Table 1, were tested in order to find the best combination to decrease both CO and PM emissions.

Table 1. Schematic table of the laboratory tests

WBT	Hole size (mm) Upper tiles	Number of rotated tiles Bottom tiles	Number of Experiments
12	5	5	1
13	4.2	5	1
14	4.2	7	1
15	5	7	1
16	4.2	3	1
17	5	3	1

5.4. Description of tested fuels

5.4.1. Wood pellets

Imported wood pellet from South Africa was used during the household test in Matola Rio, Mozambique. According to the retailer, Calore, the diameter of the wood pellets was 6 mm. The net heating value was 5 kWh/kg, the moisture content <8% and residual ash <0.5% (Calore, 2014).

The diameter of the wood pellets used during the WBT was 8 mm. According to the producers the net (lower) heating value was 5 kWh/kg, the moisture content 5-9 % and residual ash 0.5 % (CleanFlame, 2014).

Both fuels were produced from sawdust and wood shavings and did not contain any additives according to the retailers and manufacturers.

5.4.2. Birch firewood

For the WBT conducted in Sweden, birch wood was chosen because of its similar characteristics to the locally used wood in Matola Rio. The firewood for the WBT was bought at a retailer in Uppsala and cut to smaller pieces to fit the WGS. The moisture content of the birch firewood was not tested and therefore unknown. Literature says that the moisture content of birch wood stored in a dry place is estimated to be 20 % (Mytting, 2012). The heating value of birch firewood with bark and 20 % moisture content is 5 kWh/kg (18.9 MJ/kg) solid wood. The residual ash content for birch firewood without bark is 0.4 % (Lehtikangas, 1999).

5.4.3. Torrefied bamboo pellets

The torrefied bamboo pellets are made of native bamboo from the Sofala province, Nothern Mozambique. The pellets are torrefied at a temperature of 300 to 350 °C and contain 3 % maize starch binder, according to the provider (Atanassov, 2013). This fuel was used both during the WBT and during the household tests in Matola Rio.

6. RESULTS

6.1. Interviews with households

Summaries of the first and second interview are presented below.

6.1.1. Household interviews, first visit

All the participant households consisted of adults and adolescents and/or children. In each household a woman, either the mother or the eldest daughter, was responsible for the cooking. Therefore all the interviews were conducted with them. Most of the women stayed at home being responsible for the household chores. Many of the women had small shops, which they called “banco”, meaning bench. They usually had them outside their houses, close to smaller roads and pathways for favourable accessibility. Some of them sold vegetables and fruits harvested from their “machambas”, family owned piece of land for subsistence and minimal ‘cash-crop’. Others bought sandals, “capulanas” (sarongs worn by women) and other essentials from Matola and sold them at their benches. The husbands were usually working during the daytime, returning late in the afternoon.

All households visited, except one, had access to electricity. The electricity was mainly used for lamps, the refrigerator, charging mobile phones and for listening to the radio or watching TV. The household without electricity was able to charge the stove at their neighbour’s house.

Fuel and stove

All of the households used both firewood and charcoal for cooking, but charcoal was the preferred fuel because of the smokiness and soot that firewood generates. Another advantage with charcoal was that it could also be used indoors during rainy days and evenings, even though the majority of the households cooked outdoors when the weather was good enough. Some of the kitchens were located outdoors covered with tarpaulin or just a wicker wall, some had their kitchens indoors. Still the cooking could be done outdoors or indoors depending on the circumstances.

The charcoal was bought in big sacks, weighing around 75 kg at a price of 17-25 USD (550 – 800 MZN). Charcoal prices varied during the seasons of the year. During rainy seasons charcoal prices were higher because of the lack of wood. Charcoal was bought locally, often by the men while riding their bikes home from work or with a wheelbarrow in Campoane, located approximately 2 km from their households. Most of the families could only afford one sack of charcoal each month. The sack usually lasted for about 20 days; the rest of the month they had to collect firewood. Firewood was collected far from Kilometro 16. According to the women, it took one to two hours to get there. It took about one hour in order to collect 10-15 kg of firewood, followed by a home the same distance. Two of the households had access to firewood in their garden. Each of them had cut down a big tree that could supply them with firewood for their cooking practices.

The traditional stoves (charcoal stove or three stone open fire) were usually lit using coconut fibre, twigs, paper, plastic bags or paraffin oil. The main area of use for the stove was cooking and heating water for bathing. The stove was lit two to three times a day. Only the final heat after the cooking was used to heat water for bathing.

Environmental and health aspects

Many of the participant households have been living in Kilometro 16, Matola Rio for many years. All of them have sensed a massive loss of wood around the area. Around five years ago they collected firewood around the area. Finding firewood was never a problem. According to them, the loss of woods does not only depend on the increased demand for firewood, but also on the expanded use of land for construction of houses, as shown in Figure 5. Increasing charcoal prices are another indicator of decreasing abundance of wood. All of the women had sensed a major increase in charcoal prices the past few years. Five years ago a sack of 75 kg charcoal cost from 8 to 12 USD (250-400 MZN).

Figure 5. A woman who lives in the area points out places which she remembers former forestation. Today those areas are covered with houses or houses in construction. The green area to the left was just a couple of years ago forested, but has been cleared for construction.

The majority of the households did not relate their cooking practices to health issues. A few of them had experienced children burning themselves on stoves and also the stove tipping over because of the children playing too close to it. One woman had issues with her eyesight and had bleary eyes, another woman had chronic bronchitis. These diseases and illnesses were nothing they related to the cooking practices.

One out of the ten interviewed women had heard of improved cooking stoves before. One woman had seen an improved stove in a television advertisement. The stove, named Ndzilo, is smokeless and uses ethanol made out of cassava as fuel. This particular stove is well established in Maputo, where both fuel and stoves can be purchased in small local shops located around the city. An interview with Boris Atanassov, responsible for the marketing of Ndzilo, was carried out during the fieldwork in Mozambique. A summary of the interview is presented in *Wood pellets in Mozambique – an alternative to charcoal and firewood in Mozambican households* (Tabrizi, 2014). Another woman who had not heard of improved cooking stoves thought that it would be easier to obtain both improved stoves and alternative fuels in the future. All questioned also believed that it would be harder to find both charcoal in the markets and firewood for collecting in the future.

6.1.2. Second interviews, wood pellets

The very first reaction to wood pellets was that it looked like chicken dung and nothing like a fuel for kitchen practices. But after a proper introduction, it was accepted by all households.

A common critique was that the wood pellets were very smoky during ignition. This was, however, only experienced by some of the users, while others found it smokeless. The pellets were usually lit with coconut fiber and paper or plastic bags. It took quite a long time to ignite the pellets using coconut fiber and paper, which lead to an increased tendency of smoke. Plastic bags were efficient at igniting wood pellets, which caused less smoke during the lightening process.

A benefit with the wood pellets is that it does not have to be refuelled so many times during a cooking session. Most of the women refilled once per cooking session by pouring pellets from the top. This caused major development of smoke. One woman refilled her stove by pouring the ember to a metal tray, refilled the stove with pellets and topped it with the ember. Using this method to light the stove did not cause any smoke, because of the efficient ignition.

Many of the participants found it hard to cook xima and rice with the wood pellets because of its high power, which caused the kettle to boil over or burn. It was also hard, or impossible, to regulatepower. Some of the women turned the fan off to decrease the power, which lead to smoke and soot. Even though the fan was turned on during an entire cooking session, the pots turned black with soot. One of the women experienced burned rice, but by filling the stove with fewer wood pellets, she solved the problem.

Overall the wood pellets ignited quickly in the WGS, but were hard to regulate and too powerful. Smokiness is also an overall impression that many women gave. When ranging the smokiness of (1) charcoal, (2) firewood, (3) wood pellets and (4) torrefied bamboo pellets, most women answered that wood pellets were the smokiest fuel. All pots turned black during a cooking session.

It is important to keep in mind that the stoves were not optimized for wood pellets during the household tests.

6.1.3. Second interviews, bamboo pellets

Bamboo pellets were appreciated throughout the households. All of the participants were positive to this fuel, even in their initial reactions. The fuel is similar looking to traditional charcoal and therefore easily introduced to the households. The fuel in combination with the WGS was fast to light, even though it could be very smoky until fully lit. By leaving the stove outdoors until it was lit kept them from being exposed to excess smoke, but most of them ignited the stove indoors. Refuelling the stove caused a lot of smoke too. Some of the participants complained about stinging eyes during ignition and refuelling.

The users found it easy to regulate, and all of the women were overwhelmed by how fast they were able to cook their food. Most women did not see much soot on the first pot. The second pot they used during the cooking session did usually get blackened by soot.

Overall the torrefied bamboo pellets were smokeless, despite the smoke during the ignition and refuelling. Fast to ignite, easy to regulate and all participants would buy the fuel in combination with the stove if it were available at the market.

6.2. Interviews with wood industry

Secama and *Fersol* are two wood processing companies located in Maputo and Matola, respectively. The company's main area of production is furniture, gable windows, doors and other carpentry. The industry exploits a numerous of species. Chanfuta (*Afzelia quanzensis*), Umbila (*Pterocarpus angolensis*), Jambire (*Milletia sthulmannii*) are the most common species harvested. These are all noble woods, mostly harvested in the central and northern provinces of Mozambique such as Manica, Tete, Sofala and Zambezia. Fersol also imports small fractions of pines from South Africa.

The residues from production are divided into two categories: wood chippings from carpentry and sawdust from the sawmill, see Figure 6. The sawdust is sold to be used as chicken bedding. At Fersol it is packed into bags of 15kg and sold for a price of 0.3 USD (10 MZN), just to cover the expenses of packing the sawdust. When Fersol has its peak in production they pack around 50 bags of sawdust daily. During their lower production, they barely reach 10 bags. Secama used to sell their sawdust to a poultry farm, which has closed down through bankruptcy. Wood chippings are used as cooking fuel in adjoining households and hospitals. The selling of sawdust does not present a substantial income for the interviewed companies.

Figure 6. Sawdust (left) and wood chips (right) from the sawmills and carpenters.

Harvesting of forest resources is controlled by the Ministry of Agriculture in Mozambique. According to Fernando Jorge Souto at Fersol, the logging companies are only permitted to harvest forest between April and November. This means that during the summer months, Fersol does not receive sufficient timber to satisfy customer demand. Secama mentions the same problem.

Neither Sacama nor Fersol uses an oven for drying wood. Soares at Secama mentions that they have access to an oven, but they never use it. Souto says that most sawmill and carpentry companies in Mozambique are small and drying facilities are expensive. An oven would result in better drying, but the costs exceed the benefits. Therefore they leave the wood outdoors to air dry. When asked if they have thought about producing any fuels such as briquettes or pellets from the residues, the both companies say that they have not. The manager of Secama would be interested of knowing more if it could generate an income.

Souto sees the potential for contraints in the wood industry in the future. Deforestation is the biggest threat, but he thinks that it is essentially a political issue. In order to be able to harvest trees in Mozambique, a licence is required. According to Souto, this process is corrupt and poorly regulated. He has applied for a licence several times, but has been denied it each time. He says that you either have to know someone at the Ministry of Agriculture, have a lot of money or be a public figure. He ends the interview by saying that all sawmills and carpentries should keep an area of native noble wood of Mozambique, because in five years it will be in restricted supply.

6.3. Emissions

6.3.1. General observations

General observations during the WBTs are presented below.

Wood pellets

No fuel had to be added during the cold start and hot start phase of the WBT. Fuel was added twice during the simmering phase and black smoke was seen during fuel addition. The flames where also very high, reaching the handle of the pot. The pot was covered with soot after completing the WBT.

Torrefied bamboo pellets

Torrefied bamboo pellets burned smoothly and no additional fuel was required throughout the cold start, hot start and simmering tests. The fuel generated a white/grey smoke, which diminished after the fuel had been properly ignited.

Birch firewood

Birch firewood was added four times during the cold start phase and twice during the hot start phase of the WBT. The simmering phase required approximately ten refuellings. High flames and smoke was seen at the beginning, but the smoke vanished as soon as the fuel was properly ignited. The pot was black with soot by the end of the WBT.

6.3.2. Particle size distribution

In all tests conducted, the maximum number of PM was found to occur in the size range 0.3-0.5μm. For larger size ranges, with fewer recorded particles, the PM meter appears to be less accurate, as per Figure 7. The absolute error might be of the same magnitude as for larger quantities, but the relative error consequently increases. This relative error becomes even larger when taking the aerosol diluter into consideration. A relationship between the different sized channels can be seen, presented in Figure 7. The figure shows the PM size distribution for torrefied bamboo pellets, the same trend was seen for the other fuels. Because of the lack of accuracy for the larger channels, only the smallest channel, 0.3-0.5, will be presented in the forthcoming figures. Furthermore, the particles in this size range are also the most detrimental to both health and the environment.

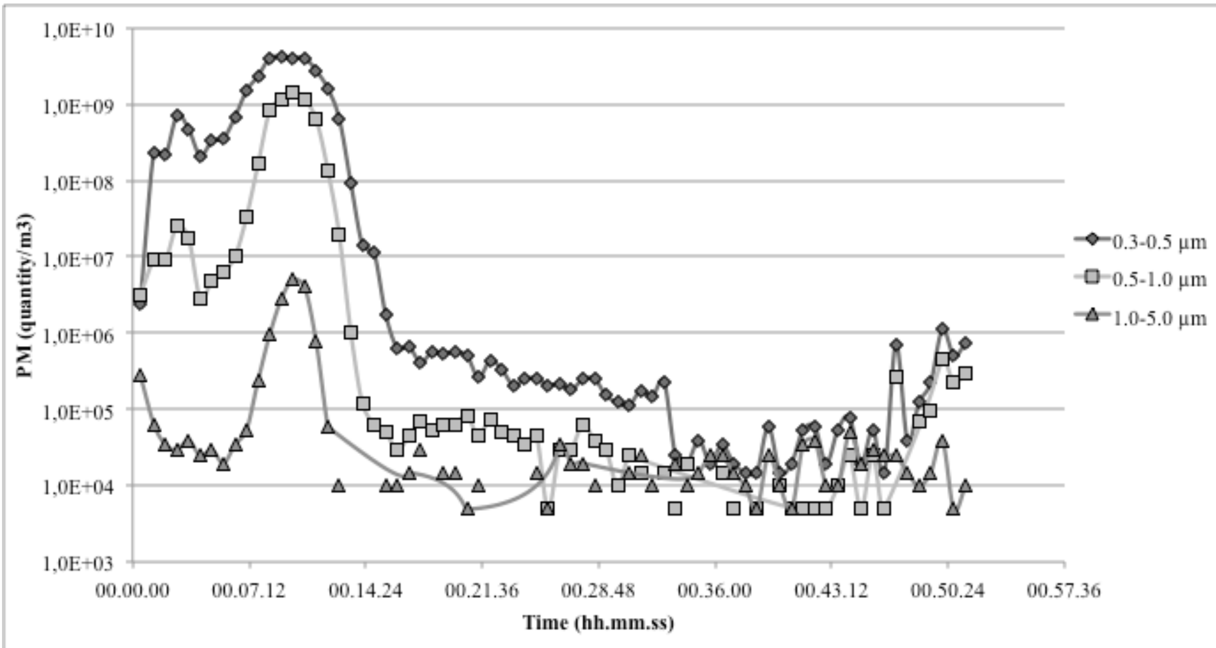

Figure 7. Size distribution of PM during a cold start test, with torrefied bamboo pellets used as fuel.

6.3.3. PM emissions

All phases of the WBT were repeated three times; an exception was the WBTs with torrefied bamboo pellet that were only repeated twice. To simplify the presentation of the phases, the test that has the most representative values, i.e. the least extreme values, is chosen and presented in the forthcoming diagrams. For example in Figure 8, WBT 2 was selected to be presented.

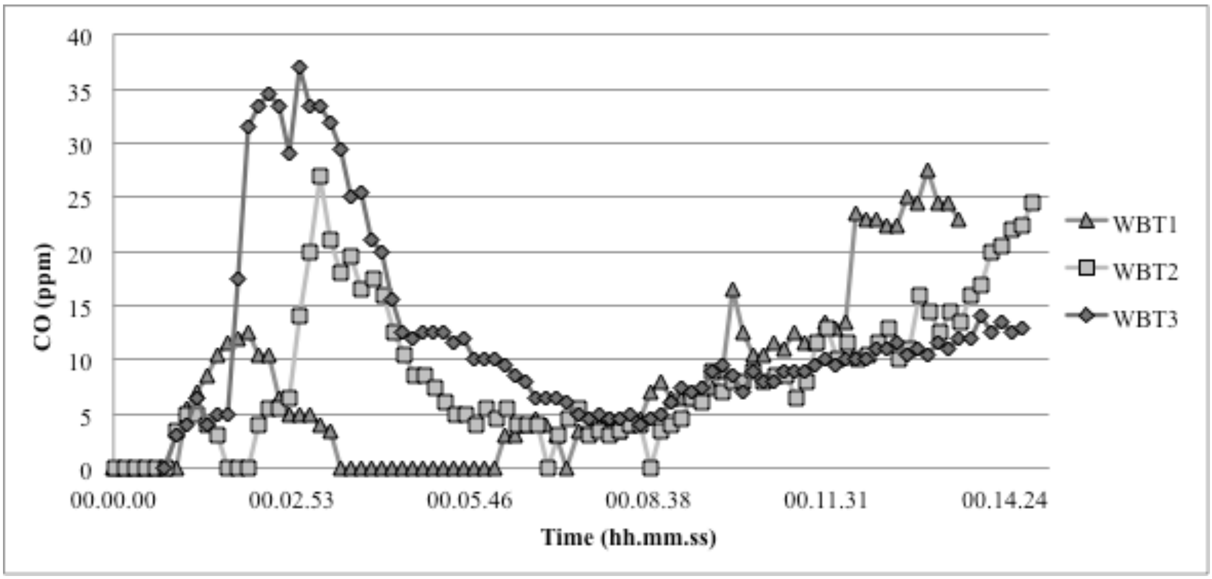

Figure 8. ***CO emissions (ppm)*** *of three WBT tests, wood pellets used as fuel. WBT 2 has the least extreme values and will therefore be presented in the forthcoming figures.*

Cold start

In all three figures presenting the PM emission during the cold start phase of the WBT, a large amount of PM is seen at the beginning of the combustion period.

Birch firewood required refuelling many times during the cold start phase, which resulted in several peaks of PM, see Figure 9. The peaks were, however, of short duration.

Torrefied bamboo pellets took time to ignite, which resulted in very high PM emissions until it was properly lit. The PM emissions were quite stable after the fuel was properly ignited. The power produced by the stove when using torrefied bamboo pellets was also low in comparison with the other fuels, and it took almost an hour to for it to bring the water kettle to boil with a lid on.

Wood pellets had quite high PM emissions during ignition, but when it was properly lit the PM emissions were at the same level as torrefied bamboo pellets.

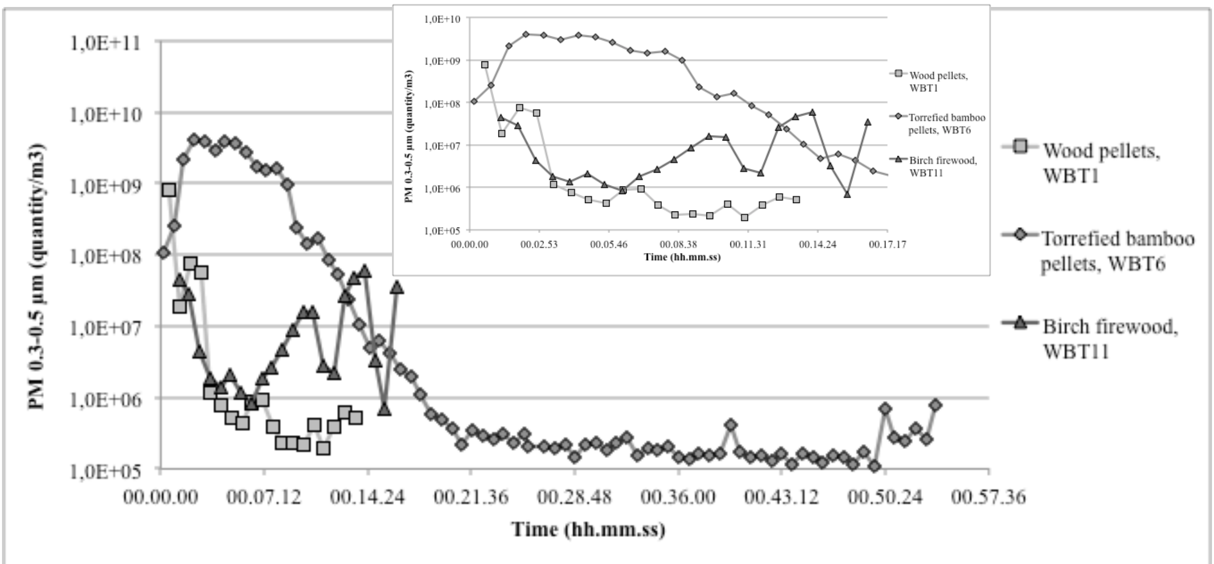

Figure 9. The quantity of $PM_{0.3\text{-}0.5}$ emitted during a ***cold start phase*** *of the WBT. Birch firewood was refuelled at the 7^{th}, 10^{th} and 14^{th} minute. (Right corner) Enlarged diagram to extract the details of wood pellets and birch firewood.*

Hot start

A high concentration of PM can be seen at the beginning of the combustion cycle, Figure 10. The large amount of PM drops quickly, followed by a slight increase towards the end. This probably occurs because of the fast ignition wood pellets had when conducting the hot start phase with wood pellets.

A peak of PM is seen during the ignition of torrefied bamboo pellets, see Figure 10. The amount of PM that developed throughout the hot start phase for the torrefied bamboo pellets were lower than for the cold start phase.

Birch firewood brought the water to boil quickly, but still required some refuellings. The refuellings were followed by peaks of PM.

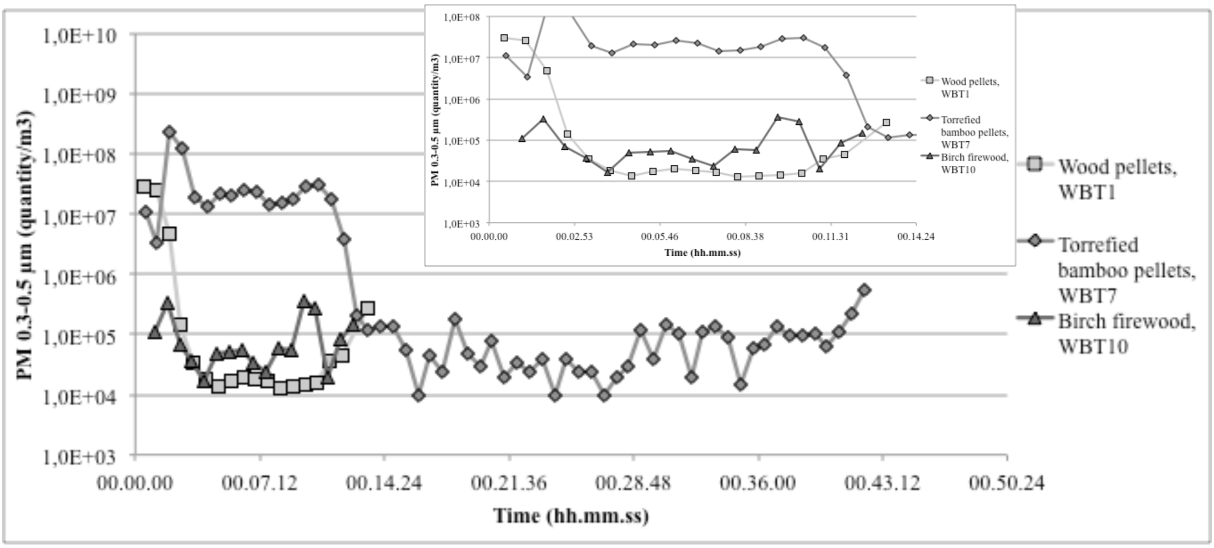

*Figure 10. The quantity of $PM_{0.3\text{-}0.5}$ emitted during a **hot start** phase of the WBT.*

Simmering

The results of PM from the simmering tests for the three fuels are presented in Figure 11.

Wood pellet was refuelled after 17 and 30 minutes. The refuellings are followed by peaks, see Figure 11.

Torrefied bamboo pellet had the highest emissions during the ignition period of the simmering test, presented in Figure 11. At approximately 7 minutes it reached the limit value of the PM meter. As in the earlier phases of the WBT, Figure 9 and Figure 10, the PM concentration decreases after the fuel has been properly lit.

Birch firewood required as many as ten refuellings. Because of the infrequent samplings, fluctuations in the curve caused by the refuellings may remain undetected.

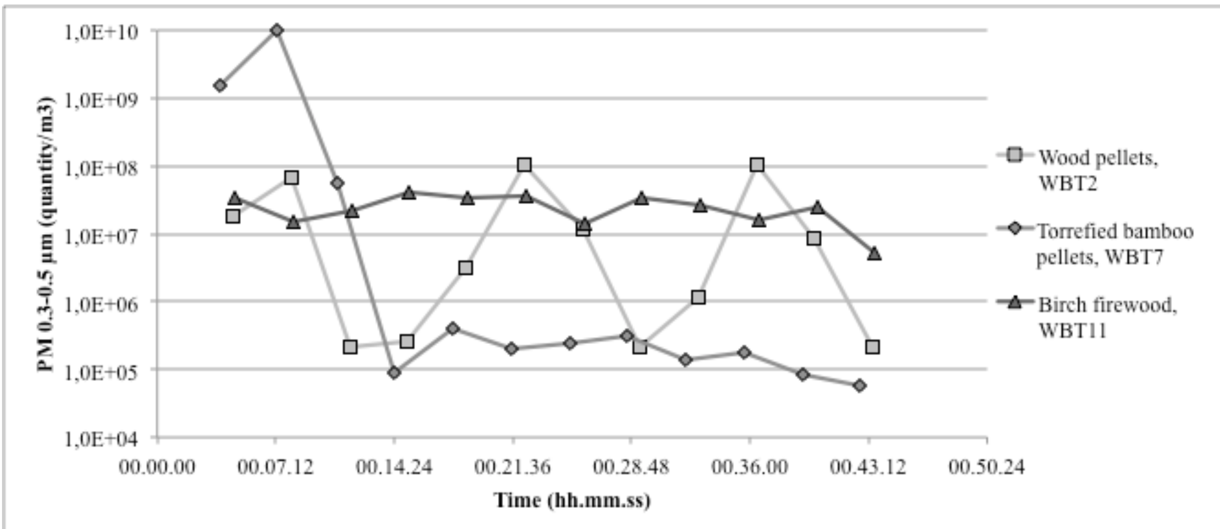

*Figure 11. The quantity of $PM_{0.3\text{-}0.5}$ emitted during a **simmering phase** of the WBT.*

6.3.4. CO emissions

Cold start

Wood pellet has its largest peak at just over 25 ppm during ignition, declining to values between 5 and 10 ppm for a period of 5 minutes. At the end of combustion there is a slight increase of CO, peaking at 25 ppm, seen in Figure 12.

Torrefied bamboo pellet has vast concentrations of CO emissions during the ignition period, with an concentration increasing to above 600 ppm until it was properly lit. After taking fire, the concentration decreased to a quite stable level of approximately 50-70 ppm. The maximum value of CO emissions during the burning cycle of torrefied bamboo pellets is almost 20 times larger than the maximum value when burning wood pellets.

Birch firewood had a quick ignition, with low concentrations of CO. The many peaks were caused by the many refuellings it required. The largest peak reached over 120 ppm, but was of short duration.

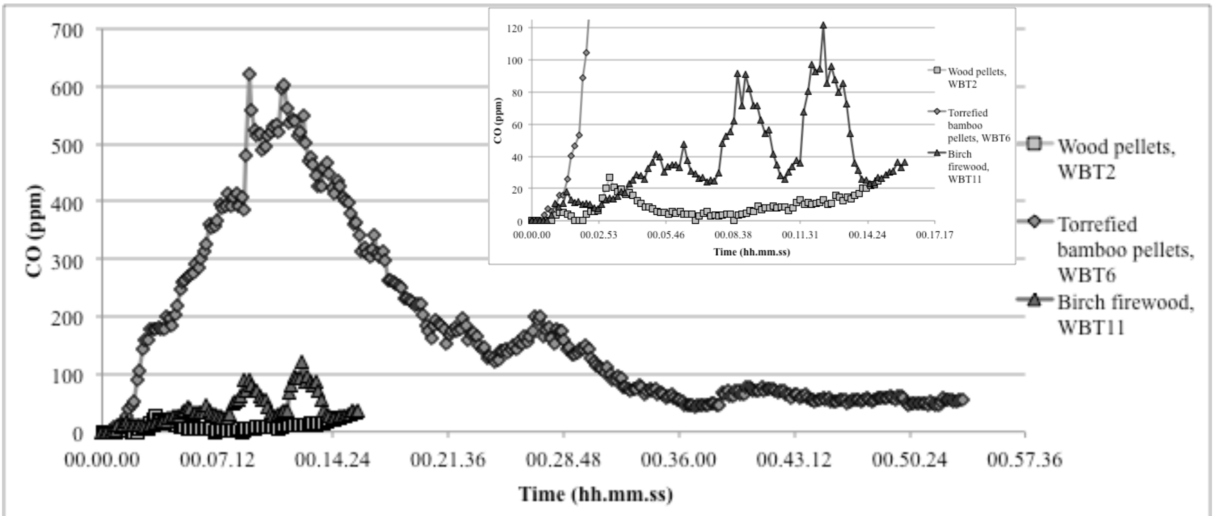

*Figure 12. CO emissions (ppm) during **a cold start phase**.*

Hot start

Lighting the torrefied bamboo pellets in the hot WGS caused high concentrations of CO. The peak reached almost 700 ppm. It did, however, not last as long as during the cold start. The CO concentrations were stabilized at a concentration of approximately 100 ppm after 20 minutes of burning, slowly declining to 50 ppm at the end of the combustion, presented in Figure 13.

The hot stove caused a rapid and rough ignition with high flames when wood pellet was used as fuel. The rapid start resulted in high temperatures and low emissions of CO at the beginning. The CO concentration escalated in step with the combustion cycle, because of the decreasing temperature.

The CO concentration for birch firewood during the hot start phase behaved similarly to the cold start phase, with various and short peaks occurring in conjunction with the numerous refuellings.

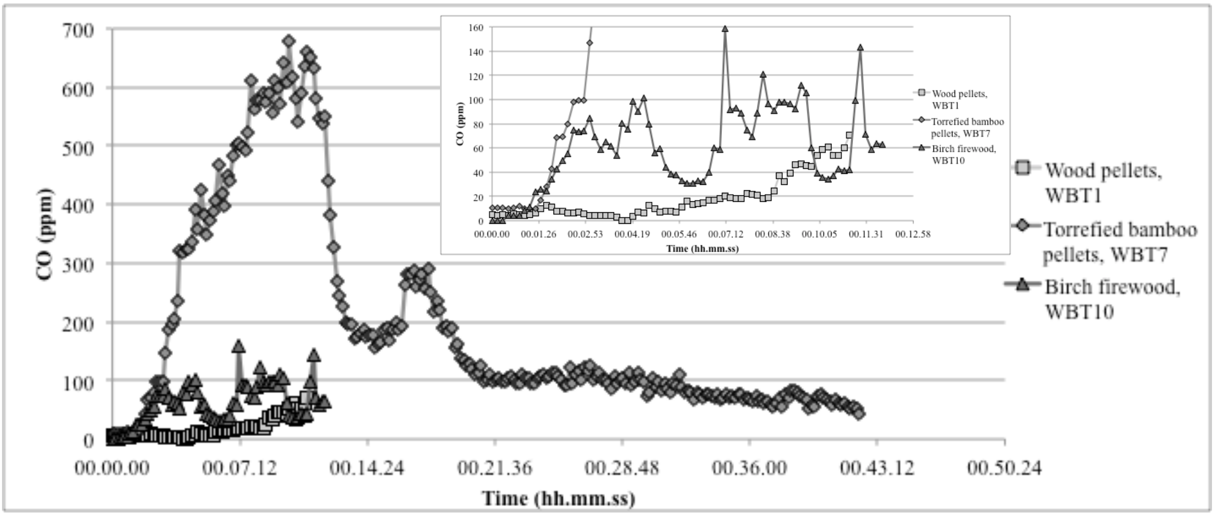

*Figure 13. CO emissions (ppm) during a **hot start** phase.*

Simmering

In addition to the peak seen during ignition of wood pellets, two further peaks can be seen in Figure 14. The highest concentration reached 130 ppm. Except these peaks, the CO concentration was quite stable, between 15 and 40 ppm.

Torrefied bamboo pellet reached the maximum limit of the CO meter of 1083 ppm during ignition, see 814. This peak of CO had, however, the shortest duration in comparison with the cold start and hot start phase.

Birch firewood required several additions of fuel and numerous of peaks mostly kept in the range of 50 and 150 ppm. Some larger peaks occurred during the simmering phase, where the largest one reached almost 350 ppm.

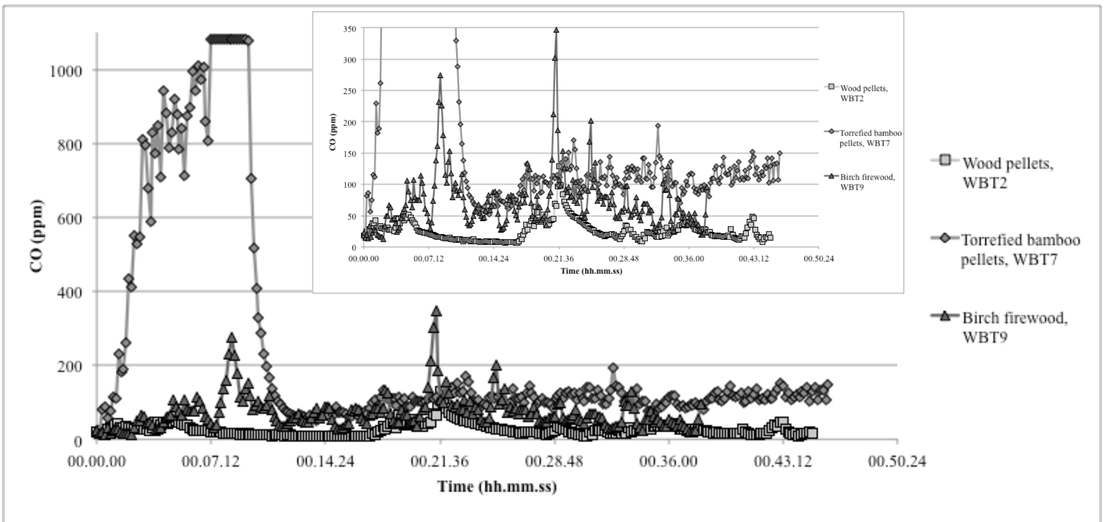

*Figure 14. CO emissions (ppm) during a **simmering phase**.*

6.4. Emissions resulting from lighting and fuel addition

To examine the impact of lighting emissions, the data of CO and PM were averaged during the lighteing period. The lighting period was set to 5 minutes for birch firewood and wood pellets. The torrefied bamboo pellets took longer to ignite and the lighting period was therefore set to 20 minutes. This lighting averaged data was compared with the average during the entire test to determine the lighting emission ratio, presented in Table 2. Emissions caused by fuel addition may have occurred later in the test. However, because of many and small fuel additions during the tests, it was not possible to allocate quantitatively emissions to these actions. The emission ratio was higher in both PM and CO for the torrefied bamboo pellets.

Table 2. Lighting emission ratio (lighting average/test average) for CO and PM during the simmering phase of the WBT

	CO (%)	PM (%)
Wood pellets, 1st test	134	43
Wood pellets, 2nd test	131	160
Wood pellets, 3rd test	139	271
Wood pellets, mean value	**135**	**158**
Torrefied bamboo pellets,1st test	141	186
Torrefied bamboo pellets,2nd test	168	171
Torrefied bamboo pellets, mean value	**155**	**179**
Birch firewood, 1st test	53	247
Birch firewood, 2nd test	53	65
Birch firewood, 3rd test	119	97
Birch firewood, mean value	**75**	**136**

6.5. Adjusted stoves

A general observation throughout all the WBTs with an adjusted stove, was that there was a black smoke tendency during ignition and addition of fuel. The flames were high during addition of fuel and the pots turned black after the tests. An exception to this was WBT 17, drilling the holes from 4.2 mm to 5.0 mm in order increase secondary airflow in combination with rotating three out of nine of the bottom tiles to lower primary airflow. No smoke was seen during the entire test and the pot showed limited signs of soot, in comparison to the other adjustments, see Figure 15. The flames where still high during addition of fuel, but approximately three minutes after addition the flames were at moderate size.

Figure 15. (left) clean pot, (middle) pot after performing WBT17, (right) pot after fulfilling WBT 14.

Since the simmering phase of the WBT is most similar to a cooking session, in comparison with the other two phases, it is chosen only to present the differences between CO and PM emissions during the simmering phase.

The results of emitted PM and CO from the adjusted stoves are presented in Figure 16 and Figure 17, respectively. As can be seen from these results, there are no substantial differences between the various adjustments and the initial setting of the stove. WBT12, WBT15 and WBT16, presented in Table 1 p. 15, had the largest CO concentration peaks.

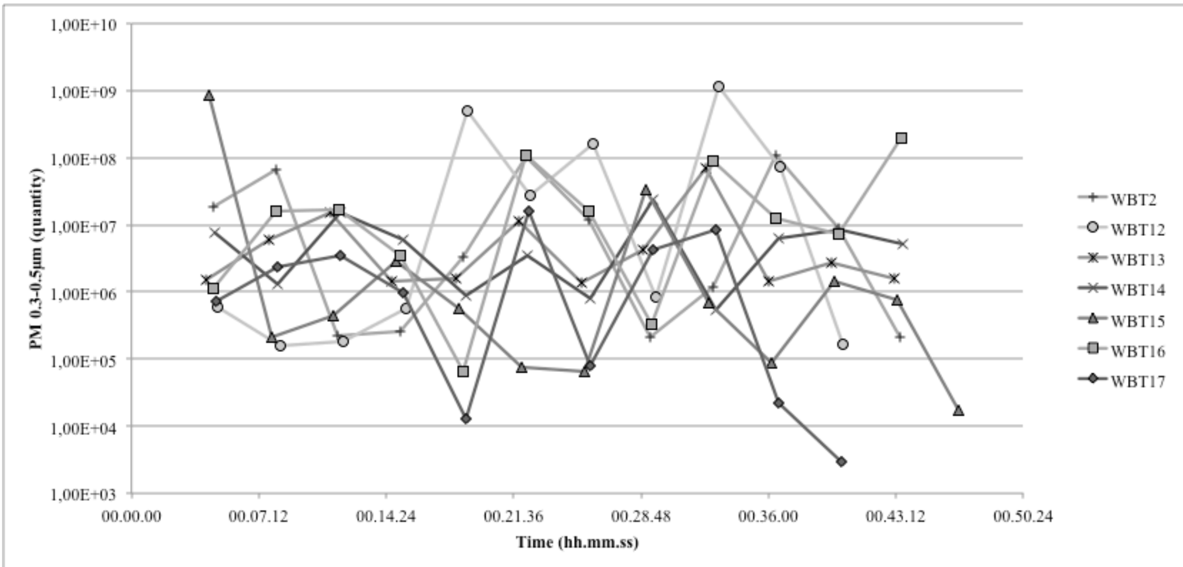

*Figure 16. **PM emissions (particles/m³)** during a simmering test, with **wood pellets** as fuel. The adjustments of the stoves can be seen in above in Table X. WBT 2 represents wood pellets in the WGS without any adjustments.*

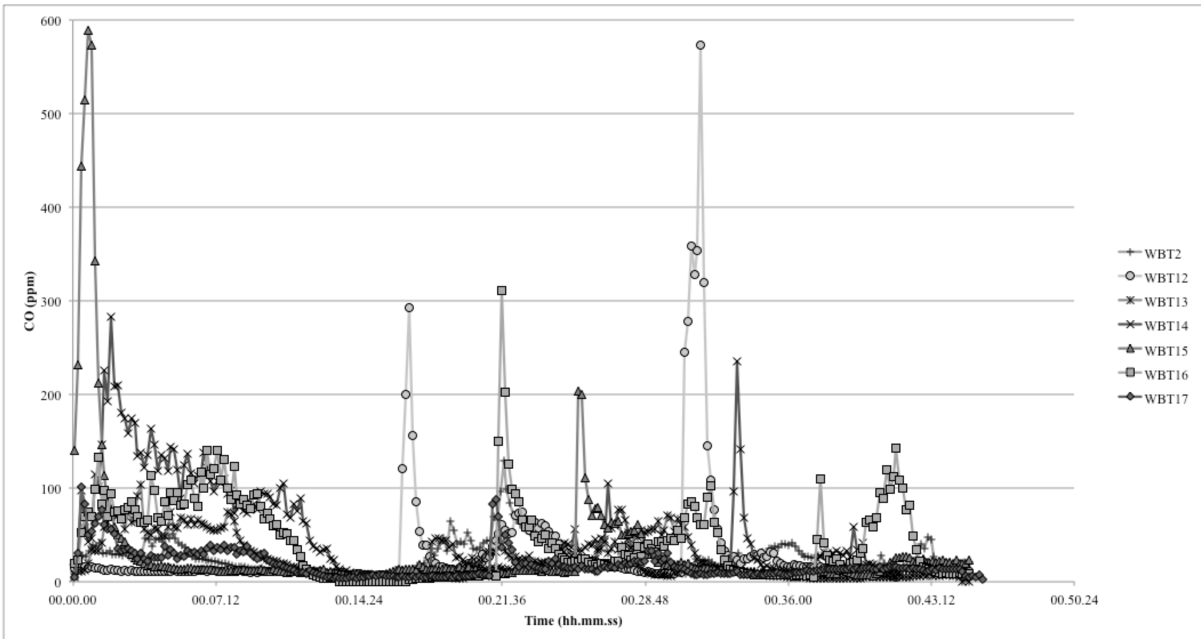

*Figure 17. **CO emissions** during a simmering test, with **wood pellets** as fuel after adjusting the stove. WBT 2 represents the CO emissions of wood pellets combusted in the WGS without any modifications.*

In a comparison of WBT 2 and WBT 17 in Figure 18, WBT 17 has slightly lower concentrations of CO with fewer peaks. This is probably because when adjusting the stove the WBT only required one refilling during the simmering phases, compared with two refuellings that WBT 2 required.

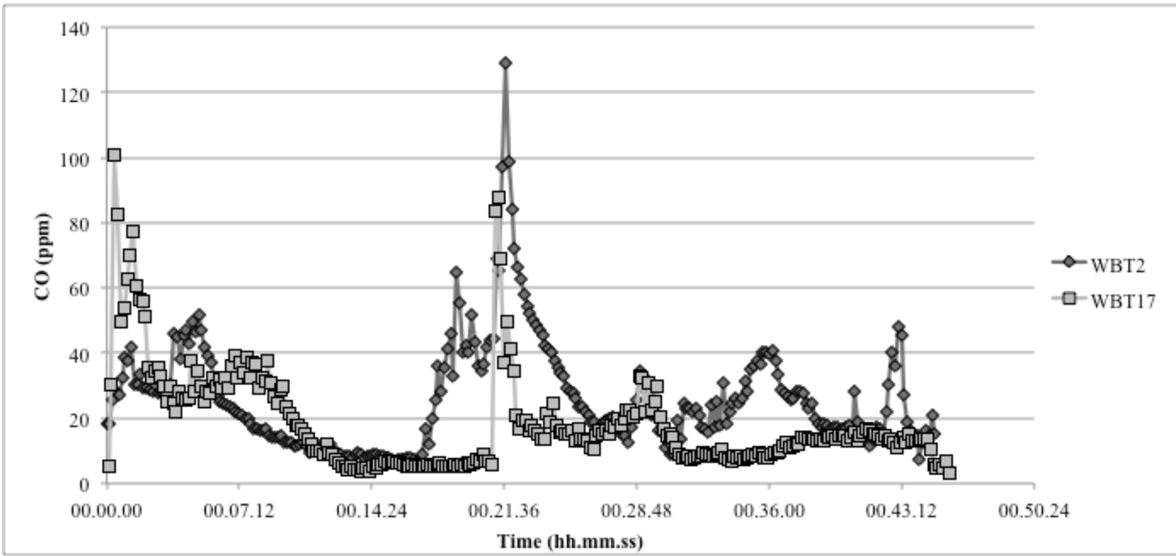

Figure 18. CO emissions (ppm) during a simmering phase.

A disadvantage with this setting was the difficulty to reach boiling point, especially during the cold start phase of the WBT. According to Tabrizi (2014) the best adjustment given the efficiency was rotating three out of nine of the bottom tiles, and the holes regulating the secondary airflow were kept to 4.2 mm.

6.6. Sources of error

There were a number of limitations to this study that might have affected the results.

- The potential for mechanically induced airflow (via the fume hood) to change the combustion characteristics of the stove and fuels.
- Temperature, pressure, relative humidity may have affected the results.
- The PM sampling during the WBT may have been affected since it was performed without a lid. Evaporated water may have influenced the PM meter.
- The WBT with torrefied bamboo as fuel had to be conducted with a lid, due to its low power. This may have affected the results.
- The PM meter was connected to an aerosol diluter. The diluter may have affected the PM characteristics, such as size. There is also a possibility that the diluter was contaminated from earlier tests. The PM diluter could also cause a slight delay during real-time measurement.
- The method used in this study for determining PM and CO only measures the emissions at a certain point. This might lead to some uncertainties, since the gases and particles are not equally distributed. The flame also varied across the tests, changing the distance between the flame and CO and PM meter.
- The PM values were printed on a thermal paper and manually transcribed to Excel. This could be an error source if the values where improperly transcribed.
- The setting of the fan to “medium” may have benefitted some fuels more than others. The exact setting of the fan may have varied between the tests as the fan has an analogue control.

- Although the pollutant concentration was measured, the actual human exposure was not examined. To fully understand the health implications of using wood pellets, torrefied bamboo pellets or firewood in the WGS, it is important to also examine patterns of exposure. The size of the PM is an important factor of how harmful the PM could be, but so is the content of the PM, which was not examined in this study.
- Variables such as lighting procedure, fuel addition, size of the birch firewood, adjustment of fan could be significant determining the emission factors.

7. DISCUSSION

7.1. Interviews

7.1.1. Households

In contrast to traditional cooking stoves in Mozambique, the WGS requires electricity in order to charge the battery, which runs the fan. This quality is a limitation for distribution of the WGS in areas that lack access to electricity. Installing local charging stations that are independent of the electricity grid, such as solar panels, could offer a solution for such areas.

Some households in Kilometro 16, Matola Rio performed their cooking indoor claiming no smoke was generated from the torrefied bamboo pellets in combination with the WGS, once the fuel was lit. The women who were interviewed are used to carrying out their cooking practices breathing in the large amounts of smoke generated from the traditional stoves. This aspect is important to keep in mind. With this factor in consideration, smokeless does not necessarily mean no smoke at all. Even if there were common illnesses and diseases among the women, which are normally associated to exposure of smoke, they did not correlate the diseases to their exposure to smoke.

Opinions on the degree of smoke development of wood pellets varied among the respondents. This, however, appears to correlate with the method and material used when lighting the fire. Coconut fibre and paper as lighting material were associated with heavy smoke while plastic bags were both more efficient in igniting the fire and less prone to smoke development. Burning plastic can emit poisonous gases, such as volatile organic compounds (VOC). It is however arguable if the reduction of PM and CO during a quick ignition with plastic is favourable over a slower ignition with biomass such as coconut fibre. By refuelling the stove with wood pellets using the “top-down method”, smoke was further reduced.

When introducing the WGS among the households, a recommendation to only fill the stove with wood pellets half way was given; this in order to allow oxygen to draft through the secondary airflow, minimizing the formation of CO. During the actual cooking practices, however, the stove was filled to the extent that the secondary airflow was blocked. Less oxygen was thereby available for reaction with the CO-rich gaseous mixture.

Torrefied bamboo pellet was the preferred fuel at the tested households. The fuel burned smooth and required less refuellings than wood pellets. A factor that could affect the results is the appearance of the fuel. Torrefied bamboo pellets are similar looking to charcoal. This could subconsciously have favoured the fuel among the testers. Nevertheless, the fuel burned smoother and the power was easier to regulate than for wood pellets in the WGS. Testing the adjusted stoves in combination with wood pellets in the households may have lead to different opinions among the women.

Implementing wood pellets as a sustainable alternative cooking fuel requires not only establishing a national production of wood pellets but also shifting from traditional cooking stoves to WGS.

7.1.2. Wood industry

Two sawmills and carpentries were visited in this study. An additional carpentry named Yola Mobílias, located in the outskirts of Maputo was supposed to be visited, but had gone out of business. This low number of wood industry participants does not give representative information for Mozambique's entire wood industry; however, an overview of the carpentries and sawmills in the outskirts of Maputo is presented.

The residues at the visited sawmills and carpentries are sold or given away, but does not generate a significant income. From an economic point of view, this facilitates the idea of introducing wood pellet plants in connection to the wood processing companies. The daily production volume of residues, such as sawdust and wood chippings, was however not high at the visited wood processing companies. Having a few carpentries and sawmills sharing the same pellet plant would probably be more profitable for the companies.

The lack of timber during the summer months means less residues at the sawmills and carpentries. This could lead to a shortage of raw material for pellet production during these months.

The expanding deforestation, especially around the urban areas, has lead to increased charcoal prices. With charcoal prices on the rise, mainly around the urban areas, wood pellet has an increased chance in competing on the market.

7.2. Emissions

Compared with the other phases of the WBT, the simmering phase is more similar to a cooking session. Nonetheless, the simmering phase is a laboratory test and is not identical to a field test. During the simmering phase, the fire was constantly tended and fuel was added frequently when needed. In real use, the primary focus is not the cooking fire; cooks are preparing food, taking care of children and other household tasks while tending the cooking fire. The simmering phase is however reasonable to use during comparison of several fuels.

Ignition and addition of fuel caused peaks of both CO and PM during the WBTs with all fuels. Why the peaks of emissions tended to be so extreme during addition of fuel can depend on the flames that reached closer to the CO and PM meter. Since the flames came closer to the meters, the concentration may appear higher because of the decreased distance to the meter and not necessarily because the CO or PM concentration rose. The large peaks could also depend on the method used for refuelling. Refuelling the stove from the top dampens the fire. When there is insufficient oxygen available there will be an increased synthesis of CO. Using a "top down" method when refuelling, i.e. emptying the stove from ember, refilling the stove with new fuel and lighting the cooking fire with ember or new lighting material, should generate less smoke and soot.

Torrefied bamboo pellets were tough to ignite in comparison to wood pellets and birch firewood. The low temperature at the beginning of the combustion cycle is the possible reason for the high concentrations of both CO and PM during ignition. The fuel is also dusty and particles from the fuel may have blown up when turning on the fan during ignition. Both PM and CO declined after a period of burning. Because of the low power of torrefied bamboo pellets and the long ignition period of the fuel, it generates a larger total amount of emissions. According to the WHO guidelines for indoor quality (2010) an adult should not be exposed to a CO concentration of approximately 115 ppm for more than 15 minutes a day. During the conducted tests, the torrefied bamboo pellets in the WGS violated this guideline.

The real time scattering of CO and PM emissions during combustion of birch firewood fluctuated during the entire test. Even if the peaks were of short duration, they recurred a numerous times. It is also inconvenient to cook with such a fuel that requires as many refuellings.

Wood pellets had the least CO emissions during the WBT. The PM emissions were high during ignition, but the quick start lead to a rapid decline of emissions. As mentioned above, refuellings caused peaks in concentration of both PM and CO.

Adjusted stove

No major differences in PM and CO emissions could be seen in the real time scattering diagrams for the adjusted stoves in combination with wood pellets, WBT12-WBT17, in comparison to WBT2, which had the initial adjustment of the stove. The PM emissions from WBT17 were kept around 10^4 and 10^7 particles/m^3,in comparison to the other adjustments that where mostly kept in the range of 10^5 and 10^8 particles/m^3. Because of the few repetitions and similar results, no conclusion can be drawn from these tests.

As presented in the results, the pot did not get blackened by soot during WBT17. It was also easier to regulate and did not bring water to boil as quickly as the initial setting of the stove. This probably would have been a better setting for the stove users when boiling rice and xima that required lower power. This adjustment did not require as many refuellings as the initial setting, which means that less wood pellets is required for a cooking session after modifying the stove. There were six different adjustments tested in this study, there might be better adjustments to the WGS, but the best adjustment tested was WBT 17 (boring the middle hole of the upper tiles from 4.2 mm to 5.0 mm and rotating three of nine bottom tiles).

8. CONCLUSION

Torrefied bamboo pellet has the highest lighting emission ratio, i.e. highest emissions during the lighting phase, compared with all tested fuels in the WGS. In spite of decreasing emissions when the fuel is properly lit, using this fuel in the WGS would violate the WHO guideline for exposure of CO.

Wood pellet is convenient to use in combination with the WGS. Wood pellets did not require so many refuellings as birch firewood and neither were the emissions as high as for birch firewood or torrefied bamboo pellets. Wood pellets had the lowest emissions of both PM and CO throughout the WBTs. To avoid the smoke tendency and increase of CO and PM emissions, the stove requires not only optimal adjustments, but also a proper operation by the cook. A "top down" burning method should be used during ignition and addition, and the stove should not be overfilled with fuel to cover the secondary airflow.

After adjustment, the stove required less refuelling as compared to the initial WGS setting. The most suitable adjustment tested in this study was as in WBT 17; expanding the holes of the upper tiles from 4.2 mm to 5.0 mm to increase the secondary airflow and rotating three of nine bottom tiles in order to decrease primary airflow. No conclusions about the adjusted stoves can be drawn from the CO and PM tests presented in the report, because of the limited number of repetitions and similar results. However, from a users point of view, adjusting the WGS as in WBT17 is the best adjustment performed in this study; lowering fuel consumption, minimising the amount of soot on the pot after cooking and for the ability to regulate stove power during cooking.

Torrefied bamboo pellet was the preferred fuel among the participated households. The fuel burned smoothly and required less refuellings than wood pellets.

9. BIBLIOGRAPHY

AFRICANCLEANENERGY. 2014. *African Clean Energy* [Online]. Available: http://www.ace.co.ls/ [Accessed 4/4 2014].

ATANASSOV, B. 2013. *RE: E-mail.* Type to VESTERBERG, J.

ATANASSOV, B., EGAS, A., FALCÃO, M., FERNANDES, A. & MAHUMANE, G. 2012. Mozambique urban biomass energy analysis 2012. Mozambique Ministry of Energy.

BAILIS, R., OGLE, D., MACCARTY, N., STILL, D., R. SMITH, K. & RUFUS, E. 2013. The Water Boiling Test (WBT). Shell Foundation.

BOND, T. C., G., S. D., YARBER, K. F., NELSON SIBYL M., WOO, J.-H. & ZBIGNIEW KLIMONT, Z. 2004. A technology-based global inventory of black and organic carbon emissions from combustion *Journal of Geophysical Research,* 109.

BOND, T. C. & RODEN, C. 2013. The Water Boiling Test - Cookstove Emissions and Efficiency in a Controlled Laboratory Setting. 4.2.2 ed.: University of Illinois.

CALORE. 2014. *Calore - Sustainable Energy* [Online]. Available: http://www.calorefireplacesandstoves.co.za/TierLanding.asp?intTierID=35 [Accessed 4/4 2014].

CLEANFLAME. 2014. *CleanFlame* [Online]. Available: http://www.cleanflame.eu/produkt/?article_id=86&lang_id= [Accessed 7/2 2014].

CRADLETOCRADLE. 2014. *Cradle to Cradle* [Online]. Available: http://www.vaggatillvagga.se/ [Accessed 3/4 2014].

EZZATI, M., LOPEZ, A. D., RODGERS, A., VANDER HOORN, S. & MURRAY, C. J. L. 2002. Selected major risk factors and global and regional burden of disease. *The Lancet,* 360**,** 1347-1360.

FAO 2010. Global Forest Resources Assessment 2010. Rome: Food and Agriculture Organization of the United Nations.

FAO. 2014. *The community's toolbox* [Online]. Food and Agriculture Organization of the United Nations. Available: http://www.fao.org/docrep/x5307e/x5307e08.htm [Accessed 4/4 2014].

HOLDREN P., J. & SMITH R., K. 2000. *World Energy Assessment: Energy and the Challenge of Sustainability*, United Nations Development Programme.

JOHANSSON, L. S., TULLIN, C., LECKNER, B. & SJÖVALL, P. 2003. Particle emissions from biomass combustion in small combustors. *Biomass and Bioenergy,* 25**,** 435-446.

LEHTIKANGAS, P. 1999. Lagringshandbok för trädbränslen. 2 ed. Kista: Sveriges Lantbruksuniversitet, Uppsala.

MAHUMANE, G., MULDER, P. & NADAUD, D. 2012. Energy outlook for Mozambique 2012-2030 LEAP-based scenarios for energy demand and power generation

MULDER, P. & TEMBE, J. 2008. Rural electrification in an imperfect world: A case study from Mozambique. *Energy Policy,* 36**,** 2785-2794.

MYTTING, L. 2012. *Hel ved: alt om huggning, stabling og tørkning - og vedfyring*, Natur & Kultur.

NHANCALE, B., MANANZE, S., DISTA, N., NHANTUMBO, I. & MACQUEEN, D. 2009. Small and medium forest enterprises in Mozambique. London, UK.

SCHUT, M., SLINGERLAND, M. & LOCKE, A. 2010. Biofuel developments in Mozambique. Update and analysis of policy, potential and reality. *Energy Policy,* 38**,** 5151-5165.

TABRIZI, S. 2014. Wood Pellets in Mozambique - An alternative to charcoal and firewood for cooking in Mozambican households. Uppsala, Sweden: Swedish University of Agricultural Sciences, SLU.

UN 2013a. The Millennium Development Goals Report 2013. New York, US.

UN 2013b. *World Statistics Pocketbook, 2013 edition,* New York, NY 10017, United States of America, United Nations.

UNDP 2013. Human Development Report 2013. New York, NY 10017, United States of America.

WHO 2006. Air Quality Guidelines - Global update 2005. Copenhagen, Denmark: World Health Organization.

WHO 2010. *WHO guidelines for indoor air quality: selected pollutants,* Copenhagen, Denmark, The World Health Organization.

10. APPENDIX

10.1. Appendix1 - Household, first visit

Objective: Get to know the current cooking situation in chosen households, reflect on their awareness of more effective alternatives for household cooking, introduce ourselves and our study and ask if they are willing to co-operate in the study.

Selection of households should be representative for the location. Talk to local chief and identify 10 HH through him/her.

Take notes on location description and description of HH.

Preparation for interview

Choose a setting with the least distraction.

Explain the purpose of the interview.

Address terms of confidentiality.

Explain the format of the interview.

Indicate how long the interview usually takes.

Provide contact information of the interviewer.

Allow interviewee to clarify any doubts about the interview.

Prepare a method for recording data, e.g., take notes.

Procedure of the interview

Occasionally verify the tape recorder (if used) is working.

Ask one question at a time.

Attempt to remain as neutral as possible.

Encourage responses.

Be careful about the appearance when note taking.

Provide transition between major topics.

Don’t lose control of the interview.

Possible questions to local chief:

- Development/highlights during the last 5 years?
- Observations about the environment (forest, land, trees outside forest etc)
- Do you know about improved wood or charcoal stoves? Which?
- Do you know how many households use an improved stove?
- What would be your priorities for the developments for the next 5 years?

Information to look for at the first HH visit

Stove

- Number of HH using ICS
- Stove condition. How are they used? How old?
- Are stoves used for space heating?

Condition of current stove

Good	Stove has no visible damage and can achieve its potential efficiency
Medium	Cracks on the body, broken door or pot rests, weakened
Poor/Bad	Worn out combustion chamber, cracks, worn out metal, missing parts, loss efficiency

Fuel

- Quantify fuel (wood, charcoal) used per head/stove type
- Any fuel collected or is all bought? Time spent collecting?
- Thoughts on fuel availability?
- Fuels used? Firewood, charcoal, kerosene, LPG, ethanol, maize cobs etc.

Environment/Health

- Cooking conditions (smokiness etc), indoors or out?
- Subjective perception of women regarding indoor air quality.
- Do they associate health problems to cooking practices?
- Accidents

Cooking practise

- Cooking time. How many times a day is the stove lit?
- Number and types of meals prepared daily
- Usage of efficient cooking methods

Observation of good cooking practices (wood)

- Using dry firewood
- Using split firewood
- Using few sticks
- Using lid on the pot
- Ash removal
- Prepare food before lighting fire
- Pre-soaking beans

Economics

- Firewood and charcoal prices; any notice of change past 5 years?
- At what proximity is the fuel bought/collected?
- Occupation of householders? Daily income?

Social

- Information channels? (Relevant for marketing). Stove dealers?
- Family size and occupation
- Type of kitchen. (Separate?)

10.2. Appendix 2 - Interviews with wood industry

(sawmills, furniture companies and other wood processing industry)

Date: ______________

Name of company (if possible): __________________

Name and title of respondent (if possible): ______________

Location: ____________________

Number of employees: _________

Topics of interest	**Problem**	**Awareness**	**Suggestion**
Line of production (lumber, furniture, floors, packaging, other)	Depending on product the moisture content can differ		
Are there any drying facilities?	Expensive and electricity-dependent		
How are the waste products being dealt with? (sold, given away, deposition, other?) Economic profit or loss?	Environmentally hazardous deposition/burning?		

Categories of waste see “Allmänna och särskilda bestämmelser för mätning av biobränslen”)	Too coarse or wet for direct pellet production?		
Is waste divided in fractions or mixed?	Better with homogenous waste		
How much waste is produced on average on a daily basis? (subjective perception if data is lacking)			

Moisture content, how wet/dry?	In need of energy-consuming drying process?		

What species of wood is used?	Hard/soft etc.		
Are the rest-products contaminated?	Can cause problems during combustion of pellets		
Distance to other facilities, such as housing areas?	Emissions from pellet production, noise, transportation		
What are the current restraints and challenges for the industry? Economical, political etc.			
Have you considered to produce densified fuels from the byproducts - such as briquettes or pellets?			
How well developed			

are the transportation routes? Compare with the transport chain of charcoal.			
Where is the raw material for the productional process provided?			

SLU
Institutionen för energi och teknik
Box 7032
750 07 UPPSALA
Tel. 018-67 10 00
pdf.fil: www.slu.se/energiochteknik

SLU
Department of Energy and Technology
P. O. Box 7032
SE-750 07 UPPSALA
SWEDEN
Phone +46 18 671000