Literature review of emissions of modern wood combustion devices and emissions reducing technologies, under real-life conditions

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Literature review of emissions of modern wood combustion devices and emissions reducing technologies, under real-life conditions

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Executive Summary

This study attempts to provide an overview of real-life emissions of wood stoves and to investigate the relationship between emissions from laboratory tests and emissions in real life. Furthermore, technologies are mapped that can possibly reduce the emissions.

The first step in the study was determining a typology of the various wood combustion appliances available on the market. In a second step, for each type of wood combustion device information was collected regarding the emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), organic gaseous carbon (OGC) and polyaromated hydrocarbons (PAH). The emission data were gathered from tests conducted under laboratory conditions, under simulated real life conditions (called pseudo real-life in this study) or effectively measured values in-house (termed as real-life conditions). These data were bundled per type of wood combustion device and are summarised in Figure S1 below.

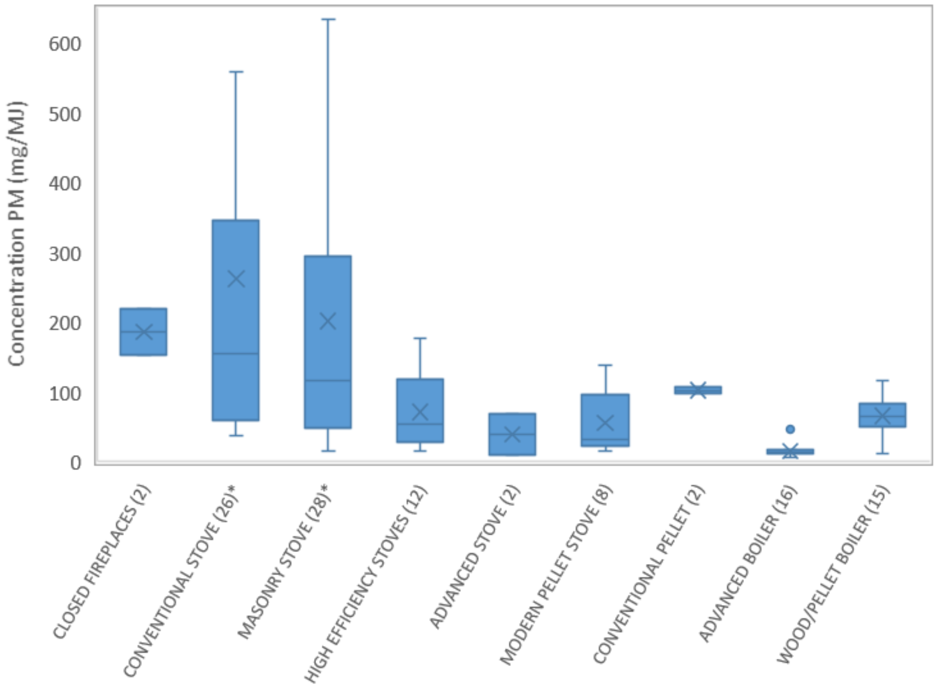


Figure S1: Boxplot summary of all data points (number given between brackets) for each type of wood combustion appliance. *category containing outliers above 1000 mg/MJ.

From the figure above, it becomes clear that PM emissions vary significantly within and between different types of devices. In general, more recent devices with newer technology show lower PM emissions compared to the older devices, which are more on the left in the graph. It is important to note that the majority of the collected data originates from tests in laboratory, either following standard test procedures or simulating real life operation. This illustrates the shortage of actual real-life data. Additionally, a lack of scientific studies on emissions from most recent stoves exists. Most tested stoves are several years old, making it difficult to estimate emissions from stoves with most recent technology incorporated.

In addition to the overview of the available wood combustion devices, an overview is also included of technology that can result in a reduction of the emissions. Two strategies exist to achieve the latter. First, it can be done by means of source control, in which especially stove design and air flow prove to be crucial elements. Source control measures typically aim to achieve optimal combustion at real operation conditions. This effect is particularly visible in the reduced emission rates of more recent stoves, which contain these types of measures. It is this effect that is visible in Figure S1. Secondly, end-of-pipe solutions can also result in reduced emissions. A widely used and commercially available technology is electrostatic precipitation. This technology is based on the collection of PM on an electrode. In practice, this appears to reduce part of the emissions, but the achieved reduction is highly dependent on the circumstances and the used stove. A second end-of-pipe solution is the incorporation of a catalyst inside the combustion chamber or inside the chimney. This is mainly effective for the reduction of CO and organic substances and is less suitable for PM. Fluctuating efficiencies are reported and in some cases, there is a risk of forming harmful by-products. Correct use and maintenance of such systems is therefore important.

An important conclusion from this literature study is that a considerable knowledge gap exists on several subjects. First of all, there is a limited amount of data collected under real-life conditions. Additionally, the interpretation and comparison of emissions in literature and in legislation appears to be difficult because of the difference in the use of units. In literature, emissions are based on energy content to allow comparisons between different types of stoves. The legislation on the other hand relies on emissions per volume of air. The latter is highly stove specific and often not known, which makes a comparison between different stoves very difficult.

Another aspect with a lot of ambiguity is the formation of secondary organic aerosols (SOA). The formation of this fraction of particulate matter occurs when the exhaust gases exit the chimney and end up in the atmosphere. Under the influence of various external factors, the organic components present in the exhaust gases will react. Consequently, a new fraction of particulate matter is formed. The concentration of SOA emissions can be of the same order of magnitude as the concentration of primary PM during the combustion process. The precise mechanism of SOA formation is very complex and dependant on various factors, making the quantification of this fraction in real life very difficult. Since SOA are formed after leaving the chimney, most tests do not measure the SOA fraction which could result in a significant underestimation of real-life emissions.

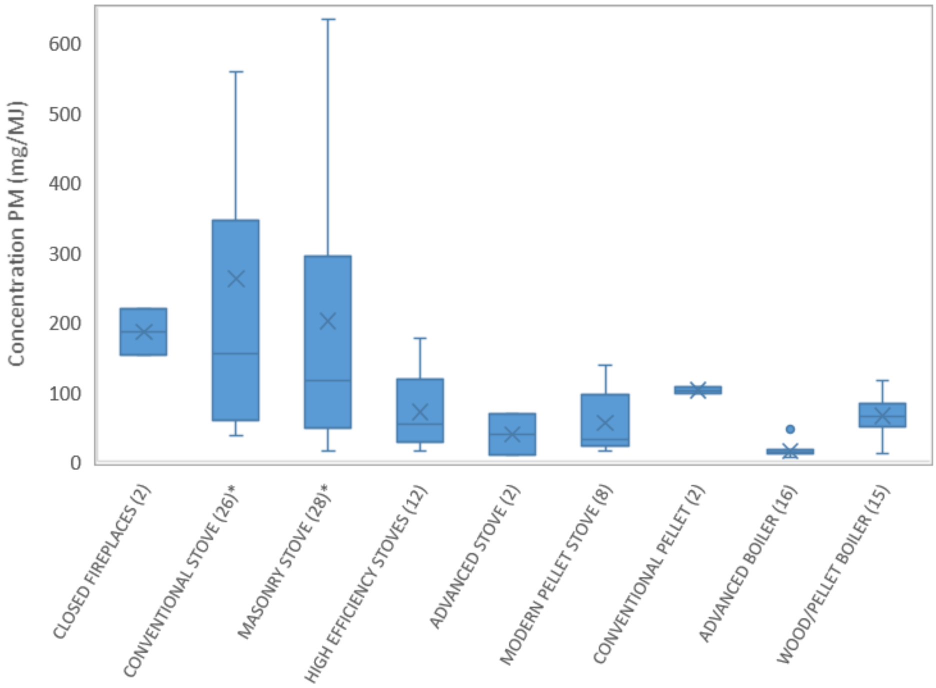
The study also provides an overview of the main causes that lead to large variations between the different testing conditions. Several aspects play a role in this variation, e.g. used technology, test method and operational conditions. The latter is mainly focused on the behaviour of the user of a wood combustion device. Elements such as the type of wood used, the degree of humidity, the fire lighting procedure etc. all have a direct influence on emissions from residential wood combustion. In the standard tests, the experimental conditions are based on the most optimal conditions while in reality a lot of the conditions are far from ideal, resulting in large differences between lab and real-life tests.

An important problem with estimating real-life emissions is that consistent information of typical or average real user behaviour is lacking. As a result, assumptions currently made in scientific literature on (pseudo) real life emissions can proof to be completely different in reality. A better understanding of these aspects is required. This can be done by performing surveys with real-life users in order to gain knowledge about their operation of a stove. Another problem is that a small fraction of real users (e.g. people burning wet, contaminated wood in old stoves) could have a relatively high contribution to the total emissions. Therefore good knowledge of best, average and worst case scenarios and their occurrence is essential to estimate the total real-life emissions.

Management samenvatting

Deze studie geeft een overzicht van de effectieve uitstoot door huishoudelijke houtverbranding en de relatie met de theoretische uitstoot gemeten in labo omgeving. Verder worden ook technologieën in kaart gebracht die de uitstoot van houtverbranding mogelijk kunnen reduceren.

In eerste instantie werd een typologie gemaakt van de verschillende houtverbrandingsinstallaties op de markt. Aan de hand van deze typologie werd informatie gezocht over de uitstoot van kachels, zowel voor fijn stof (PM) als voor andere componenten zoals koolstofmonoxide (CO), stikstofoxides (NO_x), gasvormige organische componenten (OGC) en polycyclische aromatische koolwaterstoffen (PAH). Deze informatie werd in kaart gebracht voor labotesten, die ofwel volgens de geijkte testprocedures ofwel volgens gesimuleerde reële omstandigheden plaatsvonden of voor testen die effectief in het veld bij mensen thuis gebeurden. Deze gegevens werden per type gebundeld en samengevat in Figuur S2.



Figuur S2: Boxplot overzicht van alle datapunten (aantal tussen haakjes) voor de verschillende types kachels. * Dit zijn categorieën die outliers bevatten boven de 1000 mg/MJ.

Uit de figuur blijkt dat de effectieve uitstoot voor PM zeer sterk varieert binnen en tussen verschillende types van kachel. De uitstoot van meer recente kachels, met de nieuwste technologie, is doorgaans lager dan deze van oudere kachels, die zich meer links in de figuur bevinden. Belangrijk hierbij is wel dat de meeste data onder labo-omstandigheden werden bepaald, volgens geijkte procedures of volgens gesimuleerde reële omstandigheden. Om een correct beeld te krijgen van de reële uitstoot is het nodig om houtverbrandingstoestellen ook te testen op het veld en bovendien ook de laatste nieuwe toestellen te testen. Voor de laatste nieuwe toestellen zijn er trouwens geen of nauwelijks wetenschappelijke studies voorhanden, wat het momenteel zeer moeilijk maakt om hun reële prestaties in te schatten.

Naast de beschikbare kachels werd ook een overzicht opgenomen van verschillende technologieën die in een vermindering van de uitstoot kunnen resulteren. Er zijn twee verschillende strategieën om dit te bekomen: broncontrole en *end-of-pipe* oplossingen. Bij broncontrole wordt door voornamelijk kacheldesign en luchtvoorzieningen de vorming van polluenten vermeden of verminderd. Hun direct effect is vooral zichtbaar in de verminderde uitstoot van meer recente kachels, die trachten de verbranding optimaal te laten verlopen onder reëele omstandigheden. Bij *end-of-pipe* oplossingen worden gevormde polluenten aangepakt voordat zij de schouw verlaten. Een veel gebruikte en commercieel beschikbare *end-of-pipe* technologie is elektrostatische precipitatie, die vooral effectief is in het capteren van PM. In de praktijk blijkt dit ook effectief te werken, maar de behaalde reductie is sterk afhankelijk van de verbrandingsomstandigheden en de gebruikte kachel. Een tweede *end-of-pipe* methode bestaat erin katalysatoren te incorporeren na de verbrandingskamer. Op deze manier worden vooral de uitstoot van CO en organische stoffen verminderd en minder die van PM. Ook hier zijn schommelingen in verwijderingsefficiëntie te zien. Bovendien bestaat in sommige gevallen het risico op vorming van schadelijke bijproducten. Het is dan ook belangrijk dat dergelijke systemen op een correcte manier gebruikt en onderhouden worden.

Ondanks de talrijke beschikbare informatiebronnen in verband met huishoudelijke houtverbranding blijken er ook een hele reeks kennislacunes te bestaan in het vakgebied. Vooreerst is er slechts beperkte informatie beschikbaar voor uitstoottesten uitgevoerd op het veld. Daarnaast blijkt ook de interpretatie en het vergelijken van emissies tussen literatuur en wetgeving moeilijk te zijn vanwege het verschil in gebruik van eenheden. In wetenschappelijke literatuur wordt er typisch gewerkt met eenheden gerelateerd aan de energie-inhoud, waardoor vergelijkingen tussen verschillende types van kachels mogelijk wordt. De wetgeving daarentegen baseert zich op emissies per hoeveelheid lucht. Dit laatste is echter zeer specifiek per kachel, waardoor een onderlinge vergelijking zeer moeilijk wordt. Omzetten van de ene eenheid in de andere is zeer moeilijk gezien er extra informatie noodzakelijk is die vaak niet gespecifieerd wordt.

Een ander aspect waarover nog veel onduidelijkheid bestaat, is de vorming van secundaire organische aerosolen (SOA). Deze fractie van fijn stof ontstaat in de atmosfeer, als de uitstootgassen de schouw verlaten hebben. Onder invloed van verschillende externe factoren zullen de organische componenten reageren, met als resultaat de vorming van een bijkomende fractie aan fijn stof. De concentratie van deze SOA fractie kan, afhankelijk van het soort kachel, gelijkaardig zijn aan de uitstoot van primair fijn stof en is dus niet te onderschatten. De vormingsmechanismen die hierachter zitten zijn zeer complex en afhankelijk van tal van factoren, waardoor het effectief in kaart brengen van het SOA-vormend potentieel zeer moeilijk is. Omdat SOA pas gevormd worden nadat ze de schouw verlaten, worden ze zelden gemeten in testen, wat kan leiden tot belangrijke onderschattingen van de reëele emissies.

Verder wordt er in de studie ook een overzicht gegeven van de oorzaken die ertoe leiden dat er grote variatie bestaat tussen uitstoten onder verschillende meetomstandigheden. Hierbij blijken een aantal aspecten een rol te spelen; de kacheltechnologie, de meetmethode en operationele condities. Met betrekking tot de laatste, is vooral het gedrag van de gebruiker belangrijk. Bepalende factoren zijn de gebruikte houtsoort, de vochtigheidsgraad van het hout, de aanmaakprocedure… Bij de geijkte testprocedures gebeurt de verbranding steeds onder optimale omstandigheden die sterk afwijken van het reële gebruik. In de praktijk zijn de verschillende factoren vaak niet optimaal. Als gevolg hiervan kunnen grote verschillen ontstaan tussen gemeten uitstoten en werkelijke uitstoten.

Een belangrijk probleem bij het schatten van de reële uitstoot is dat er geen eenduidige informatie over gemiddeld of typisch gebruikersgedrag bestaat. Als gevolg hiervan worden momenteel in de wetenschappelijke literatuur aannames gemaakt over (gesimuleerde) reële uitstoot die volledig verschillend zouden kunnen zijn van de realiteit. Om de noodzakelijke extra kennis hieromtrent te vergaren, kunnen enquêtes uitgevoerd worden bij gebruikers over hun werkelijke stookgedrag en –gebruiken. Een volgend probleem is dat een klein deel van de werkelijke gebruikers een groter dan gemiddeld aandeel hebben in de totale uitstoot ten gevolge van houtverbranding door suboptimaal stookgedrag door bijvoorbeeld nat of behandeld hout stoken in oude installaties. Om een realistische schatting te maken van totale werkelijke uitstoot is het om die reden essentieel om optimale, gemiddelde en slechte gebruiksscenario’s en hun relatieve belang te kennen.

Content

Executive Summary II
Management samenvatting V
Content VIII
List of Figures IX
List of Tables X
1. Introduction 1
2. Scope and definitions 3
2.1. Stove typology 3
2.2. Emissions reduction technologies 5
2.3. Testing conditions for measurements of emissions 5
2.4. Studied emissions 6
3. Information of emissions per type 8
4. Strategies for emission reduction 24
4.1. Source control 24
4.2. Electrostatic Precipitator 25
4.3. Catalytic converter 27
4.4. Ceramic filters 29
5. Impact of emissions on the atmospheric concentration 30
5.1. Secondary Organic Aerosol Formation 30
5.2. Real-life implementations on a larger scale 31
6. Knowledge gaps & future research needs 33
6.1. Lack of data under real-life conditions 33
6.2. Comparison of data is challenging 33
6.3. Effective impact on air quality 34
7. Towards characterisation of real-life conditions 35
8. Policy Advice 39
9. Conclusion 41
10. References 42

List of Figures

Figure 3-1: Overview of PM emissions of closed fireplaces and conventional wood stoves. (AIR) with the reference indicates air starved experiments. 9

Figure 3-2: Overview of PM emissions of masonry stoves. 12

Figure 3-3: Overview of PM emissions of high-efficiency conventional stoves and advanced combustion stoves. 14

Figure 3-4: Overview of PM emissions of modern pellet stoves and conventional boilers. 16

Figure 3-5: Overview of PM emissions of advanced boilers. 18

Figure 3-6: Overview of PM emissions of wood/pellet boilers. 20

Figure 3-7: An overview of the number of references found per emission measurement condition and per type of appliance. 22

Figure 3-8: Boxplot summary of all data points (number given between brackets) for each type of wood combustion appliance. *category containing outliers above 1000 mg/MJ. .23

Figure 5-1: Overview of the burning process of wood combustion focused on PM10. Adapted after (Nussbaumer 2017). 30

List of Tables

Table 1-1: Current Belgian requirements for new combustion devices regarding minimum efficiency level and maximum CO and PM emissions, measured at 13% O2, TS 15883. .. 1

Table 1-2: European eco-design directive with maximum emissions for different pollutants emitted by different RWC devices, at 273 K and 1 013 mbar at 13 % O_2. 2

Table 3-1: Overview of closed fireplace emissions of PM, CO, OGC/PAH and NO_x. 10

Table 3-2: Overview of reported conventional wood stove emissions of PM, CO, OGC/PAH and NO_x. 10

Table 3-3: Overview of masonry stoves emission factors for PM, CO, NO_x and OGC/PAH at different testing conditions. 13

Table 3-4: Overview of emission factors for PM, CO, OGC, PAH and NO_x of high-efficiency stoves 15

Table 3-5: Overview of emission factors for PM, CO, OGC, PAH and NO_x of advanced combustion stoves 15

Table 3-6: Overview of PM, CO, NO_x and OGC/PAH emissions of modern pellet stoves ..17

Table 3-7: Overview of PM, CO, NO_x and OGC/PAH emissions of conventional boilers. ...17

Table 3-8: Overview of PM, CO, OGC/PAH and NO_x emission factors of advanced boilers. 19

Table 3-9: Overview of pellet boiler emissions of PM, CO, OGC/PAH and NO_x emissions.21

Table 3-10: Overview of emissions data collected from all different types of wood appliances with unit mg/MJ. 23

Table 4-1: Overview of removal efficiency based on the IEA report of Task 32. Most tests are conducted under laboratory conditions. Where available, real-life tests were included. 26

Table 4-2: Achieved removal efficiencies for TSP and PM_1 and effective TSP concentration in the flue gas for the different tested wood combustion devices (Thomas Brunner, Wuercher, and Obernberger 2017). 27

Table 6-1: Overview of units for emitted pollutant concentrations from wood combustion devices used in scientific literature. 33

Table 6-2: Table containing conversion calculation based on (Skreiberg 2002). 34

1. Introduction

The Flanders Environment Agency (*Vlaamse Milieumaatschappij* – VMM) recently reported that in a winter campaign in Dessel approximately one third of PM_{10} in the air could be attributed to wood combustion (Vlaamse Milieumaatschappij 2016; Van Poppel et al. 2017). Besides PM, other pollutants as polyaromatic hydrocarbons (PAHs), NO_x and volatile organic compounds (VOC) are also reported to be part of the emissions due to residential wood combustion (RWC) (Kaivosoja et al. 2012; WHO 2015). Associated with RWC caused air pollution are health problems related to lung malfunctioning, but also carcinogenic and cardiovascular effects are suggested (Kocbach Bølling et al. 2009; WHO 2015; Van Poppel et al. 2017). Besides effects on human health, RWC is also known to be a large source of black carbon, which is an important substance contributing to the problem of global warming (Carvalho 2016; WHO 2015).

Recent awareness about the negative effects of RWC initiated the introduction of a campaign by the Flemish Government to inform people on how to use a wood stove in a smart and responsible way with the introduction of www.stookslim.be. Beside this, the Flanders Environment Agency also started with an information campaign in which it asks people not to burn wood during periods of bad air quality (www.vmm.be/stookadvies). Furthermore, the Federal public service Health, Food Chain Safety and Environment started checking stoves available on the Belgium market to verify their compliance with current legislation. The Belgian legislation [KB 2010/24412] describes the requirements for new heating devices burned with solid fuels, amongst which minimal efficiency levels and maximum CO and PM emissions (Table 1-1).

Table 1-1: Current Belgian requirements for new combustion devices regarding minimum efficiency level and maximum CO and PM emissions, measured at 13% O2, TS 15883.

	Minimum efficiency level [%]		Maximum CO emissions [%]		Maximum particulate emissions [mg/Nm³]	
Operation mode	Continuous	Not continuous	Continuous	Not continuous	Continuous	Not continuous
Free-standing stove (NBN EN 13240)	65	75	0,8	0,1	150	40
Enclosed stove (NBN EN 13229)	65	75	0,8	0,1	150	40
Heat accumulating device for solid fuels (NBN EN 15250)	75		0,1		40	
Pellet device (NBN EN 14785)	80		0,02		30	
Boiler stove (NBN EN 12809)	75		0,1		150	
Boiler (NBN EN 303-5)	75		1,5		100	
Open fireplace (NBN EN 13229)	65		0,8		300	

Based on the conformity tests, non-compliant stoves are taken out of the market. Next to the testing, the federal public service Health, Food Chain Safety and Environment also published a list of all stoves currently sold on the Belgian market with some basic information regarding their emissions. Currently (21/12/2017), 3047 different devices are permitted in Belgium, as can be seen on the website of the federal public service (https://www.health.belgium.be/nl/e-services/lijst-van-verwarmingstoestellen).

Beside the Belgian legislation, there is also the European eco-design directive, specifying emissions standards for wood combustion devices based on three different types, which will come into force in 2022. An overview of the values can be found in Table 1-2.

Table 1-2: European eco-design directive with maximum emissions for different pollutants emitted by different RWC devices, at 273 K and 1 013 mbar at 13 % O_2.

Type of RWC device	CO (mg/Nm³)	PM (mg/Nm³)	OGC (mg C/Nm³)	NO_x (mg/Nm³)
Open front	2000	50	120	200
Close front, no pellets	1500	40	120	200
Close front, pellets	60	20	60	200

All conformity tests are currently executed under laboratory conditions, in controlled facilities with strict control of i.a. fuel type. The question arises how representative these tests are for emissions from stoves installed inside a household and operated by an average end-user. This literature study tries to identify the difference between lab emissions tests and real-life operation emissions. Beside this, an overview of emission reduction techniques is given, also based on real-life emissions tests. Missing information in current literature is identified and important aspects surrounding current knowledge are summarised. Altogether, this results in policy recommendations to ensure that the current knowledge gap related to residential wood combustion can be filled in the near future.

2. Scope and definitions

This report will consider different types of stoves and wood combustion technologies, so it is important to define a uniform typology of the different systems available on the market. Based on common literature several different divisions can be made, for example based on the technology behind the stove (EEA 2016) or based on the typology used by the federal public service (FOD, Health n.d.).

In this report, the typology is based on the EMEP/EEA air pollutant emission inventory guidebook to make international comparison possible.

2.1. Stove typology

Open fireplaces

These are not considered.

Partly-closed fireplaces

These are not considered.

Closed fireplaces

Closed fireplaces are equipped with front doors and have air flow control systems, which include the distribution of combustion air to primary routes (grate) and secondary routes (panels), as well as a system to discharge the exhaust gases. The retention time of the gases in the combustion zone is longer compared with open fireplaces. They are prefabricated and installed as stand-alone units or as a fireplace inserts installed in existing masonry fireplaces (EEA 2016).

Conventional, radiating stoves

Stoves are enclosed appliances in which hand supplied fuels are combusted to provide useful heat, which is transmitted to the surroundings by either radiation or convection. Convection stoves work through heat storing and accumulation. Radiating stoves can be fired with wood and both down-burning and up-burning methods are used. These appliances typically have poorly organised combustion process resulting in low efficiency (40% to 50%) (EEA 2016).

Masonry stoves

Masonry stoves are always a combination of bricks and/or stones and fireproof materials such as ceramic. Due to the large thermal capacity of masonry materials they keep a room warm for many hours (8-12) or days (1-2) after the fire has burnt out. Their combustion chamber can be equipped with horizontal strips or inclined, perpendicular baffles made of steel or fireproof material, which improve combustion quality and efficiency. Because of the increased residence time of fuels in the combustion zone there is a decrease in pollutant emissions compared to conventional radiating stoves. Their combustion efficiency ranges from 60% to 80% (EEA 2016).

High-efficiency conventional stoves

High-efficiency conventional stoves essentially cover traditional stoves with improved utilization of secondary air in the combustion chamber.

As a sub-category of high-efficiency stoves, it is possible to equip stoves with a catalytic converter in order to reduce emissions caused by incomplete combustion, this is particularly the case for wood fuel based stoves. The catalytic converter (a cellular or honeycomb, ceramic substrate monolith covered with a very thin layer of platinum, rhodium, or combination of the two) is usually placed inside the flue gas channel beyond the main combustion chamber. The catalyst efficiency in emission reduction depends on catalyst material, its construction – active surface area, and the conditions of flue gas flow inside the converter. Due to more complete oxidation of the fuels, energy efficiency also increases. However the catalyst will need frequent cleaning in order to maintain its performance (EEA 2016).

Advanced combustion stoves

Advanced combustion stoves are characterized by multiple air inlets and pre-heating of secondary combustion air by heat exchange with hot flue gases. This design results in increased efficiency (near 70% at full load) in comparison with the conventional stoves (EEA 2016).

Modern pellet stoves

Modern pellet stoves are a type of advanced stove using an automatic feed for pelletized fuels such as wood pellets, which are distributed to the combustion chamber by a fuel feeder from small fuel storage. Modern pellets stoves are often equipped with active control system for supply of the combustion air. They reach high combustion efficiencies by providing the proper air/fuel mixture ratio in the combustion chamber at all times (CITEPA, 2003). As a result, they are characterised by high efficiency (between 80% and 90%) (EEA 2016).

Conventional boilers

In general, boilers are devices which heat water for indirect heating. They are mainly intended for generation of heat for the central heating system (including hot air systems) or hot water, or a combination of both. Solid fuel conventional boilers include both over-fire boilers and under-fire boilers, a differentiation based on the organisation of their combustion process. Over-fire and under-fire boilers use all types of solid fuels except pellets and wood chips (EEA 2016).

Advanced boilers

Two types of installations are included in this category of wood combustion devices: advanced, under-fire boilers and downdraught wood boilers. The former is similar to conventional under-fire boilers, but in this case flow of primary and secondary air are controlled by a fan. Downdraught wood boilers have two chambers: first one where fuel is fed for partial devolatilisation and combustion of the fuel layer and a second one where the released combustible gases are burnt. In downdraught boilers, combustion air and flue gases are controlled with a fan. Some devices use lambda control probes to measure flue gas oxygen concentration and have precise combustion air control and staged-air combustion (EEA 2016).

Wood / pellet boilers

Automatic log-fired boilers are available, although most small boilers are wood pellet or chip-fired. These devices have a fully automatic system for feeding of pellet or woodchip fuels and for supply of combustion air, which is distributed into primary (beneath the grate) and secondary (into the gas oxidation zone) air supplies. The burners can have different design such as underfeed burners, horizontally fed burners and overfed burners (EEA 2016).

2.2. Emissions reduction technologies

In some of the described types of wood combustion devices, different emission reduction strategies are already implemented. For example, in some of the high-efficiency stoves catalytic converters are implemented. Another possible strategy to reduce emissions is an automatic regulation of the air influx into the combustion chamber, based on the temperature and oxygen content of the flue gas, so that the combustion process can be optimised.

In general, two different approaches for emissions reduction, each based on a different assumption, can be identified: source control and end-of-pipe solutions. Both strategies will be taken into account and the focus will be on the aspects described below.

Source control

Reducing residential wood combustion pollutants via source control implies avoiding or diminishing pollutant formation during the combustion process. To achieve this, it is of upmost importance to improve the control over the combustion process. Therefore, most innovative stoves are equipped with the necessary sensors to obtain information about temperature and oxygen content. Using this information, air intake can be automatically controlled to ensure an optimised combustion.

Another strategy for source control is trying to reduce end-user errors. This can be achieved by for example incorporating smart systems, aimed at giving information about how much wood should be added to the fire at what time, in order to ensure that the stove will continue operation under optimal combustion conditions. Some systems even stop functioning when the wood is too humid, in order to prevent suboptimal operation.

End-of-Pipe solutions

In end-of-pipe solutions for pollutant emission reduction, pollutants that are formed during the combustion process are targeted and treated before they reach the atmosphere. In this report, the following technologies are selected and studied as end-of-pipe strategies (Obernberger and Mandl 2011)

- Electrostatic Precipitators (ESPs)
- Catalytic converters
- Filters

2.3. Testing conditions for measurements of emissions

In this report the focus lies on the emissions of stoves under real-life operation, but often other testing procedures are used. Therefore, it is necessary to exactly define which elements are included and which are not for the different possible procedures. In the continuation of this report, the different testing conditions are categorised as in the definitions below.

The first type of tests are measurements conducted in a laboratory using the methodology and procedure described in the standard EN 13240. These tests are designated as laboratory experiments.

Pseudo real-life conditions are the test circumstances in which measurements are executed in a laboratory, but the methodology and procedure is based on the typical behaviour of an end-user. For pseudo real-life conditions no testing specifications are defined, making comparison between different experiments difficult.

Real-life conditions are measurements conducted in the field. This implies that the experiments are executed with a stove present inside a residential building and based on the end-users' normal procedure of lighting, refilling and ending a heating cycle. Real-life condition tests are the most realistic ones, but are clearly dependent on the specific conditions which can vary largely between different use cases. This results in difficulties with comparisons of different real-life condition experiments. The execution of these test can be done either by the end-user themselves or by an external researcher.

2.4. Studied emissions

Particulate matter

Particulate matter (PM) is a diverse mixture of small solid particles or liquid droplets. PM exists in different sizes and can be grouped accordingly into PM_{10}, $PM_{2.5}$, PM_1 and UFP (ultra fine particulates). The particles have an aerodynamic diameter smaller than 10 µm, smaller than 2.5 µm, smaller than 1 µm and smaller than 0.1 µm, respectively. Chemically, PM is a combination of organic and inorganic particles. In the case of wood combustion, organic carbon and soot are the two most prevalent components of PM. Another categorisation of PM can be made according to its formation process. Primary PM is the PM that is formed immediately during the combustion. Secondary organic aerosols on the other hand, are formed via condensation or photochemical oxidation of organic gaseous compounds emitted in the air. In scientific literature, particulate matter is often measured as $PM_{2.5}$ or as TSP. TSP is defined as total suspended particles, which comprises all particles, i.e. all sizes and all compositions.

In general, PM is associated with detrimental health effects such as decreased lung functioning, infections of the respiratory tracks and asthma. The current scientific view is that the smaller a particle is, the more harmful it is due to the fact that smaller particles can migrate deeper in the lungs. In Flanders, the VMM estimates that 71% of the loss of healthy life years caused by environmental pollution can be attributed to PM_{10} and $PM_{2.5}$. . Besides the effects on human health, PM is also known to have an effect on to climate change.

The main focus of the studied emissions lies on particulate matter because of its important contribution to the total emission of PM in Flanders (VMM 2016).

CO

Carbon monoxide is an odourless and colourless gas that is formed due to incomplete combustion, when oxygen is insufficiently present. When CO is present in higher concentrations, it limits the amount of oxygen transported in the human body. This can possibly result in dizziness, over unconsciousness to eventually death. Important sources of outdoor carbon monoxide are devices that burn fossil fuels, industry and wood combustion devices.

OGC

Organic gaseous carbon (OGC) is a collective term for all sorts of substances that exist in ambient air as gas or as vapour. OGC originating from wood combustion include a variety of pollutants going from benzene and formaldehyde to oxygenated organic compounds as ketones and phenols. OGC are known to negatively affect our health as carcinogenic compounds, but furthermore they also have a great impact on our environment. In the presence of nitrogen oxides (NO_x), OGC can result in the formation of tropospheric ozone. OGC can also act as precursors for the formation of secondary organic aerosols.

PAH

Polycyclic aromatic hydrocarbons (PAHs) are the pollutants with condensed benzene cores that can exist bound to particles or in the gas phase. The more volatile PAHs are a part of what is understood as organic gaseous carbon. PAHs are mentioned separately in this report for two reasons. First, residential wood combustion is a major source of PAH emissions and secondly, PAHs are known to be harmful for human health. PAHs exist naturally in coal, tar and oil, but are also formed due to incomplete combustion of organic matter and fossil fuels. The most recent data suggest that wood combustion makes up 57% of total benzo(a)pyrene emissions in Flanders (https://www.vmm.be/lucht/infografieken/infografiek-houtverbranding.jpg). In this report, where possible special attention will be given to benzo(a)pyrene (B(a)P) as an indicator of PAHs in general. This substance is well-studied and known to be carcinogenic and therefore emphasised in regulation.

NO_x

Nitrogen oxides comprise both NO and NO_2. NO_x are formed by reaction between nitrogen and oxygen at high temperatures. This can happen naturally, for example by volcanic activity or lightning, but also anthropogenically during combustion processes. In the latter case, three different NO_x formation mechanisms exist. Thermal NO_x and prompt NO_x formation result from the presence of nitrogen in the air, while fuel NO_x is formed from nitrogen that is present in the fuels. In case of residential wood combustion, only fuel NO_x is formed due to the fact that combustion temperatures are not high enough to result in other NO_x-formation mechanisms. NO_x are environmentally important pollutants since they contribute to tropospheric ozone formation, acidification and photochemical smog. Additionally, exposure to NO_x can result in respiratory tract irritation.

3. Information of emissions per type

Categorisation of the investigated wood combustion devices into a certain type as described in Paragraph 2.1 is difficult due to the minimal description of the tested devices in scientific literature. As a consequence, it is impossible to focus the literature review specifically on devices available on the Belgian market. To overcome this, the scope of the examined literature is broadened to European studies, in the assumption that they report about devices present on the European market and that these appliances are similar to the ones present on the Belgian market. Important to remark is that Belgian legislation on residential wood combustion devices is currently more strict than most other European countries. As a consequence, it is possible that some of the devices listed below are not allowed on the Belgian market.

The examined scientific papers are grouped below in tables depending on the type of wood combustion device. In the first column the author and year of the publication are reported. Columns two, three and four specify the circumstances in which the research has taken place: test conditions, combustion air supply and fuel type. The next columns present the reported emission values for PM, CO, OGC/PAH and NO_x.

In general, not all studies investigated emissions of all pollutants considered in this report, which makes comparison difficult. Furthermore, not all types of wood combustion are examined to a similar extent. The more recent a certain technology is, e.g. advanced combustion stoves, the less this technology is studied in scientific papers. In this report, this results in tables of varying length.

Closed fireplaces

Closed fireplaces have not been extensively studied in Europe, as can be deduced from Table 3-1. The only study that investigated the emissions from closed fireplaces was executed by Ozgen et al. Compared to the emissions reported in the EMEP 'Air pollutant emission inventory guidebook 2016', Ozgen et al. reported lower PM and B(a)P emissions and higher NO_x and CO emissions (Table 3-10) (Ozgen et al. 2014). It has to be noted that they tried to mimic real life operation, which could be an explanation for the variation in emission factors per pollutant and the deviation from the EMEP values. Additionally, the presented emission factors are averaged over the combustion cycle, but temporally higher peak values can be expected due to fuel feeding, which does not happen automatically in the tested closed fireplace.

Conventional wood stoves

Emission factors of conventional radiating stoves are studied by different authors. In general, one can conclude from Figure 3-1 and Table 3-2 that wide variations exist in the emission factors of the different pollutants that are listed. When the collected data are compared to the values reported in the EMEP 'Air pollutant emission inventory guidebook 2016', it can be concluded that the emission factors reported in the EMEP guidebook fall in the intervals of emission factors collected in this report (Table 3-10). The main reason for the diverging emission factors is the different testing procedures and conditions used in different studies. Other variables that can explain the deviation between different emission factors, like fuel type or type of wood, do not lead to clear conclusions regarding their effect on emission factors. One conclusion however can be postulated: air starvation in the combustion chamber leads to increased emission of the different pollutants with a factor two.

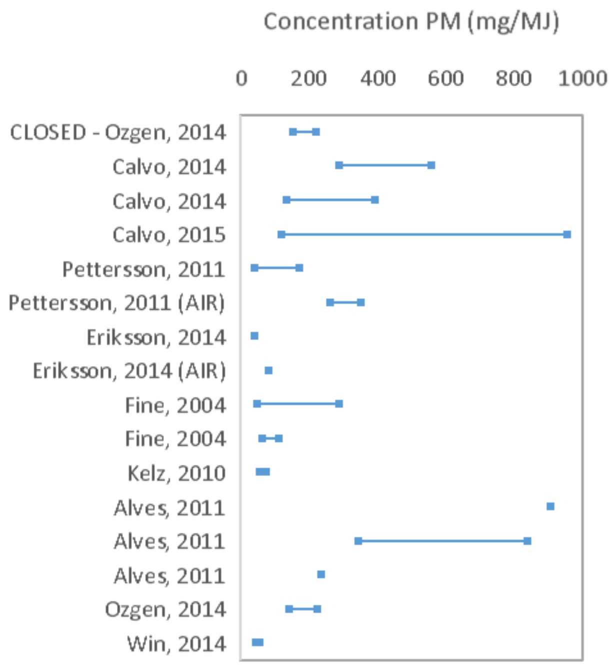


Figure 3-1: Overview of PM emissions of closed fireplaces and conventional wood stoves. (AIR) with the reference indicates air starved experiments.

Table 3-1: Overview of closed fireplace emissions of PM, CO, OGC/PAH and NO_x.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					800 mg TSP/MJ	4000 mg/MJ	0.121 mg B(a)P/MJ	50 mg/MJ
(Ozgen et al. 2014)	PSEUDO REAL LIFE	Manual operation	HW + SW logs	Normal	152-219 mg PM/MJ	3949-5030 mg/MJ	0.014 mg B(a)P/MJ	105-140 mg/MJ

Table 3-2: Overview of reported conventional wood stove emissions of PM, CO, OGC/PAH and NO_x.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					800 mg TSP/MJ	4000 mg/MJ	0.121 mg B(a)P/MJ	50 mg/MJ
(Schmidl et al. 2011)	LAB	Manual operation	Softwood briquettes	Normal	150.9 mg PM_{10}/Nm^3	1331 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Beech logs	Normal	111.4 mg PM_{10}/Nm^3	2779 mg/m^3		
(Schmidl et al. 2011)	LAB	Manual operation	Oak logs	Normal	107.3 mg PM_{10}/Nm^3	2948 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	Normal	156.6 mg PM_{10}/Nm^3	2240 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	Air-starved	488.7 mg PM_{10}/Nm^3	3971 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	High fuel load	178.1 mg PM_{10}/Nm^3	2370 mg/Nm^3		
(Calvo et al. 2014)	LAB	Manual operation	Eucalyptus logs	Normal	286-559 mg PM_{10}/MJ	3175-3862 mg/MJ		
(Calvo et al. 2014)	LAB	Manual operation	Pine logs	Normal	132-394 mg PM_{10}/MJ	2726-2915 mg/MJ		
(Calvo et al. 2015)	LAB	Manual operation	Mixture HW logs	Normal	118-955 mg $PM_{2.5}$/MJ	2833-5744 mg/MJ		
(Pettersson et al. 2011)	LAB	Natural draft	HW + SW logs	Normal	38-170 mg TSP/MJ	1100-3400 mg/MJ	1.3-9.8 mg PAH/MJ	35-66 mg/MJ
(Pettersson et al. 2011)	LAB	Natural draft	HW + SW logs	Air-starved	260-350 mg TSP/MJ	7100-7200 mg/MJ	45-220 mg PAH/MJ	35-38 mg/MJ
(Eriksson et al. 2014)	LAB	Natural draft	Birch logs	Normal	40 mg TSP/MJ	520-5600 ppm	0.1 mg PAH/MJ	

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
(Eriksson et al. 2014)	LAB	Natural draft	Birch logs	Air-starved	80 mg TSP/MJ	920-19000 ppm	0.7 mg PAH/MJ	
(Evtyugina et al. 2014)	LAB	Manual operation	Mixture HW logs	Normal		3389-5778 mg/MJ		
(Avagyan et al. 2016)	LAB	Natural draft	HW + SW logs	Normal			0.0325 mg PAH/MJ	
(Avagyan et al. 2016)	LAB	Natural draft	HW + SW logs	High fuel load			0.218 mg PAH/MJ	
(Fine, Cass, and Simoneit 2004)	REAL LIFE	Manual operation	HW logs	Normal	48-189 mg $PM_{2.5}$/MJ			
(Fine, Cass, and Simoneit 2004)	REAL LIFE	Manual operation	SW logs	Normal	61-111 mg $PM_{2.5}$/MJ			
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Logwood	Normal	55.5-74.2 mg PM_1/MJ	2086-2355 mg/MJ	185.7-223.9 mg OGC/MJ 4.561-8.786 mg PAH/MJ	
(Alves et al. 2011)	LAB	Manal operation	SW logs	Normal	906 mg $PM_{2.5}$/MJ			
(Alves et al. 2011)	LAB	Manual operation	HW logs	Normal	344-839 mg $PM_{2.5}$/MJ			
(Alves et al. 2011)	LAB	Manual operation	Briquettes	Normal	233 mg $PM_{2.5}$/MJ			
(Ozgen et al. 2014)	PSEUDO REAL LIFE	Manual operation	HW + SW logs	Normal	140-225 mg PM/MJ	6059-11131 mg/MJ	0.122 mg B(a)P/MJ	91-110 mg/MJ
(Win and Persson 2014)	LAB	Unknown	SW pellets	High power, medium power & low power	43-55 mg PM2.5/MJ	16-48 mg/MJ		60-63 mg/MJ

Masonry stoves

In Table 3-3, the emission factors for masonry stoves from recent literature are reported. When the collected data are compared to the emission factors from EMEP's 'Air pollution emission inventory guidebook 2016', it can be observed that the EMEP values all lie between minimum and maximum of the collected emission factors, except for NO_x (see also in Table 3-10). The NO_x emission factor in the EMEP guidebook is lower than the range of NO_x emissions reported in scientific literature. Mutually comparing the results of the different studies is difficult since the different authors all investigated different parameters that explain variation in emission factors. Tissari et al. focused on different operation behaviour, Nuutinen et al. investigated different sizes and ages of masonry stoves and Fine et al. looked for the effect of type of wood. Tissari et al. concluded that smouldering conditions (lack of air) result in a drastic increase in PM, OGC and CO emissions compared to normal operation (Tissari et al. 2008). Emission factors of these pollutants are up to ten times higher under smouldering conditions. The comparison between different sizes of masonry stoves learns that the effect of size depends on the age of the device: in older masonry stoves, increase in size resulted in higher emissions, while this effect is not noticed with modern stoves (Nuutinen et al. 2014). At last for type of wood, i.e. softwood vs hardwood, no clear results are obtained by Fine et al. with respect to the lowest emission factors.

Comparing the reported emission factors from conventional, radiating stoves with masonry stoves learns that PM and CO emissions for both types of wood combustion devices are of a similar order of magnitude. Reported NO_x emissions from masonry stoves are higher than those from conventional radiating stoves.

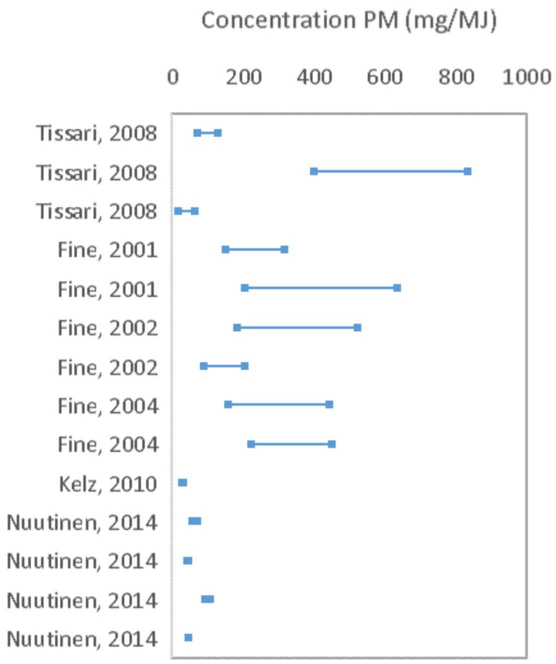


Figure 3-2: Overview of PM emissions of masonry stoves.

Table 3-3: Overview of masonry stoves emission factors for PM, CO, NO_x and OGC/PAH at different testing conditions.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMAP/EEA					800 mg TSP/MJ	4000 mg/MJ	0.121 mg B(a)P/MJ	50 mg/MJ
(Tissari et al. 2008)	LAB	Manual operation	Birch wood	Optimal	72-128 mg PM_1/MJ	2111-2556 mg/MJ	100-144 mg OGC/MJ	72-83 mg/MJ
(Tissari et al. 2008)	LAB	Manual operation	Birch wood	Smouldering	400-833 mg PM_1/MJ	5833-10 611 mg/MJ	940-2500 mg OGC/MJ	72 mg/MJ
(Tissari et al. 2008)	LAB	Manual operation	Birch wood	Normal	16-62 mg PM_1/MJ	1137-1308 mg/MJ	24-276 mg OGC/MJ	
(Fine, Cass, and Simoneit 2001)	REAL LIFE		HW logs		150-317 mg $PM_{2.5}$/MJ		1.44 mg PAH/MJ	
(Fine, Cass, and Simoneit 2001)	REAL LIFE		SW logs		206-633 mg $PM_{2.5}$/MJ		6.44 mg PAH/MJ	
(Fine, Cass, and Simoneit 2002)	REAL LIFE		HW logs		183-523 mg $PM_{2.5}$/MJ		3.45 mg PAH/MJ	
(Fine, Cass, and Simoneit 2002)	REAL LIFE		SW logs		89-206 mg $PM_{2.5}$/MJ		5.95 mg PAH/MJ	
(Fine, Cass, and Simoneit 2004)	REAL LIFE		HW logs		156-444 mg $PM_{2.5}$/MJ		14.10 mg PAH/MJ	
(Fine, Cass, and Simoneit 2004)	REAL LIFE		SW logs		222-450 mg $PM_{2.5}$/MJ		8.00 mg PAH/MJ	
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Logwood		28.0 – 31.3 mg PM_1/MJ	1008-1207 mg/MJ	52.4-69.2 mg OGC/MJ 0.081-0.099 mg PAH/MJ	
(Nuutinen et al. 2014)	LAB	Conventional, small	SW logs	Normal	56.3 – 69.1 mg/MJ	1872 mg/MJ	332 mg OGC/MJ	
(Nuutinen et al. 2014)	LAB	Modern, small	SW logs	Normal	40.2 – 44.5 mg/MJ	703 mg/MJ	96 mg OGC/MJ	
(Nuutinen et al. 2014)	LAB	Conventional, medium	SW logs	Normal	94.1 - 106 mg/MJ	3747 mg/MJ	Out of Range mg OGC/MJ	
(Nuutinen et al. 2014)	LAB	Modern, medium	SW logs	Normal	44.5 – 44.8 mg/MJ	703 mg/MJ	83 mg OGC/MJ	

High-efficiency conventional stoves

Emission factors of high efficiency conventional stoves are studied by different authors and are presented in Figure 3-3 and Table 3-4. Comparison between different studies is difficult given the fact two different units for the emissions are used and data is lacking for conversion between the two units. Secondly the different studies aimed at investigating different parameters, which results in different testing conditions. For example, Boman et al. examined the effect of fuel load and could conclude that emissions from low fuel loads are higher than high fuel loads (Boman et al. 2011). Furthermore, Schmidl et al. found that air starved operation of high efficiency stoves results in higher emissions of the different pollutants compared to normal operation and high fuel load operation (Schmidl et al. 2011). When the emission factor ranges are compared to those in EMEP's 'Air pollution emission inventory guidebook 2016', no clear relation is found. PM emission factors in EMEP are higher compared to those reported in Table 3-4, for NO_x the reverse is true. This can easily be observed in Table 3-10.

At last, emission factors from high efficiency stoves are compared to those of conventional stoves. High efficiency stoves perform better than conventional stoves when PM (and CO) are considered. On the other hand, NO_x (and PAH) emissions from high efficiency stoves sometimes appear to be higher than in conventional radiating stoves.

Advanced combustion stoves

Advanced combustion stoves are not often scientifically investigated, as can be deduced from Table 3-5. One reason might be that these appliances are the most recent type of wood combustion devices, so only in most recent studies these appliances can be examined. PM and CO emissions reported by Tissari et al. are both lower than the emissions in EMEP's 'Air pollutant emission inventory guidebook 2016', which can also be seen in Table 3-10 (Tissari et al. 2008).

When PM and CO emissions of advanced combustion stoves are compared to those emissions from high efficiency stoves, it can be observed that in general emissions of advanced combustion stoves are lower.

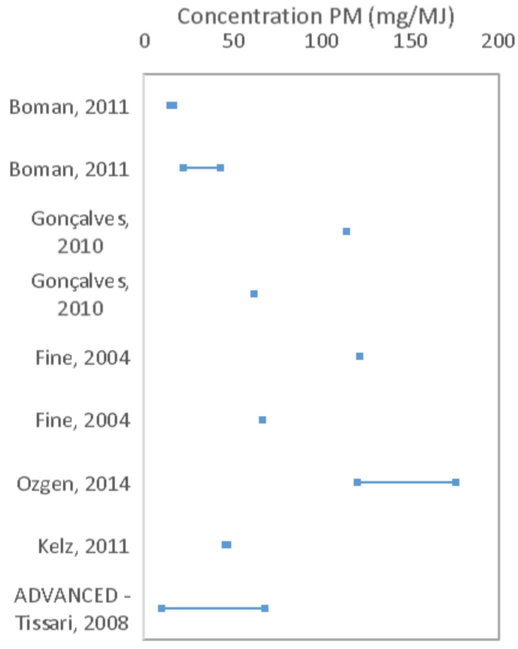


Figure 3-3: Overview of PM emissions of high-efficiency conventional stoves and advanced combustion stoves.

Table 3-4: Overview of emission factors for PM, CO, OGC, PAH and NO_x of high-efficiency stoves

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					400 mg TSP/MJ	4000 mg/MJ	0.121 mg B(a)P/MJ	80 mg/MJ
(Schmidl et al. 2011)	LAB	Manual operation	Softwood briquettes + logwood	Normal	115.5-131.3 mg PM_{10}/Nm^3	1491 - 3074 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	Normal	128.3 mg PM_{10}/Nm^3	2161 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	Air starved	146.7 mg PM_{10}/Nm^3	2841 mg/Nm^3		
(Schmidl et al. 2011)	LAB	Manual operation	Spruce logs	High load	78.9 mg PM_{10}/Nm^3	1989 mg/Nm^3		
(Boman et al. 2011)	LAB	Air staged combustion	SW logs	High load	15-17 mg PM_{tot}/MJ	100-160 mg/MJ	3.3- 41 mg PAH /MJ	
(Boman et al. 2011)	LAB	Air staged combustion	SW logs	Low load	22-43 mg PM_{tot}/MJ	310 – 770 mg/MJ	90 – 340 mg PAH/MJ	
(Gonçalves et al. 2010)	LAB	Manual operation	HW logs	Normal	114 mg PM_{10}/MJ		1.65 mg PAH/MJ	
(Gonçalves et al. 2010)	LAB	Manual operation	SW logs	Normal	62 mg PM_{10}/MJ		9.04 mg PAH/MJ	
(Fine, Cass, and Simoneit 2004)	REAL LIFE	Manual operation	HW logs	Catalyst	122 mg $PM_{2.5}$/MJ		0.000319 mg PAH/MJ	
(Fine, Cass, and Simoneit 2004)	REAL LIFE	Manual operation	SW logs	Catalyst	67 mg $PM_{2.5}$/MJ		0.000652 mg PAH/MJ	
(Ozgen et al. 2014)	PSEUDO REAL LIFE	Manual operation	SW + HW logs	Normal	120-176 mg PM_{tot}/MJ	4885-7829 mg/MJ	0.152 mg B(a)P/MJ	99-182 mg/MJ
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Wood log		46.1-47.2 mg PM_1/MJ	1036-1048 mg/MJ	94.2-95.5 mg OGC/MJ 0.263-0.466 mg PAH/MJ	

Table 3-5: Overview of emission factors for PM, CO, OGC, PAH and NO_x of advanced combustion stoves

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					100 mg TSP/MJ	2000 mg/MJ	0.010 mg B(a)P/MJ	95 mg/MJ
(Tissari et al. 2008)	LAB	Unique grate	Birch wood	Normal	9.7-68.05 mg PM_1/MJ	731-824 mg/MJ	18.2-26.3 mg OGC/MJ	

Modern pellet stoves

Pollutant emissions from different modern pellet stoves are shown in Figure 3-4 and listed in Table 3-6. Important to remark is that not all authors expressed the pollutant emissions in the same unit, which makes comparison of emissions difficult. From the collected data that can be compared with emission factors in EMEP's 'Air pollution emission inventory guidebook 2016', it can be concluded that all reported EMEP emission factors lie in the range of the collected emission factors (see also Table 3-10). The comparison between pseudo real-life data and lab data does not lead to clear relations from which general extrapolation can be conducted. A conclusion that can be made however is that also for modern pellet stoves air starvation conditions result in highest emissions of all pollutants compared to optimal conditions (Eriksson et al. 2014), just like with high efficiency stoves and masonry stoves.

Conventional boiler

In Figure 3-4 and Table 3-7 the emission factors for conventional boilers are presented. As can be deduced from the table, not much recent literature on this subject is present. Kelz' simulated real life operation emission of PM was lower compared to the emission factor in EMEP's 'Air pollutant emission inventory guidebook 2016', but the opposite is true for CO and PAH emissions, as can be observed in Table 3-10 (Kelz et al. 2010). No general relations between lab data and pseudo real life data can be determined, since for each 'category' only one set of data is present. The comparison between conventional boilers and conventional wood stoves learns that PM and PAH emissions of conventional boilers are lower, and CO emissions of boilers are higher than those of conventional wood stoves.

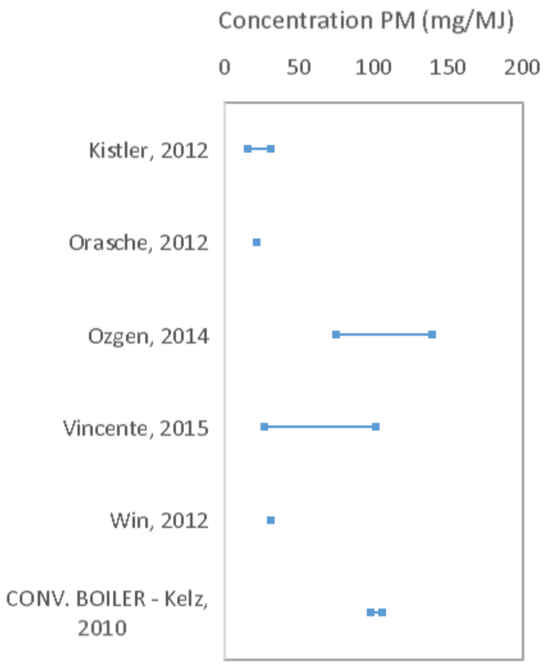


Figure 3-4: Overview of PM emissions of modern pellet stoves and conventional boilers.

Table 3-6: Overview of PM, CO, NO_x and OGC/PAH emissions of modern pellet stoves

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					62 mg TSP/MJ	300 mg/MJ	0.010 mg B(a)P/MJ	80 mg/MJ
(Schmidl et al. 2011)	LAB	Manual operation	SW pellets	Following EU standard	9.9 mg PM_{10}/Nm^3		15.17 mg/Nm^3	124.67 mg/Nm^3
(Eriksson et al. 2014)	LAB	Not specified	SW pellets	Optimal combustion		20-850 ppm	<0.1 mg PAH/MJ	
(Eriksson et al. 2014)	LAB	Not specified	SW pellets	Air starved		730 – 16000 ppm	0.5 mg PAH/MJ	
(Kistler 2012)	LAB		Wood pellets		16-31 mg PM_{10}/MJ			
(Orasche et al. 2012)	LAB	Automatic control	Spruce pellets	Normal	22 mg PM_{tot}/MJ	413 mg/MJ	10 mg OGC/MJ 0.000077 mg B(a)P/MJ	165 mg/MJ
(Ozgen et al. 2014)	PSEUDO REAL LIFE	Automatic control	Pellets	Normal	75-139 mg PM_{tot}/MJ	73-108 mg/MJ	0.0015 mg B(a)P/MJ	32-90 mg/MJ
(Vicente et al. 2015)	LAB		Pellets		26.6 – 102 mg/MJ			
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	80 % of nominal power (12 kW)	31 mg PM/MJ	192 mg/MJ		61 mg/MJ

Table 3-7: Overview of PM, CO, NO_x and OGC/PAH emissions of conventional boilers.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					500 mg TSP/MJ	4000 mg/MJ	0.121 mg B(a)P/MJ	80 mg/MJ
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Logwood	Real life simulation	98.6-106.1 mg PM_1/MJ	8969-12 632 mg/MJ	650.8-1143.8 mg OGC/MJ 3.39-18.85 mg PAH/MJ	

Advanced boiler

Collected PM, CO, OGC/PAH and NO_x emission factors of advanced boilers are presented in Figure 3-5 and Table 3-8. In general, it can be concluded that the PM and CO emission factors in EMEP's 'Air pollutant emission inventory guidebook 2016' are higher than the collected PM and CO emissions data, while EMEP's emission factors for PAH and NO_x are in the collected interval of emission factors (see also in Table 3-10). In general, the only clear conclusion that can be made from comparing the pseudo real life experiments with the laboratory experiments is that PAH emissions from lab tests are lower than those from pseudo real life tests. Furthermore, Kelz et al. investigated the effect of fuel type on pollutant emissions for an advanced boiler operated under simulated real life conditions. From these experiments it can be concluded that the use of pellets results in lower emissions than wood chips and log wood (Kelz et al. 2010). Lamberg's experiments on effect of fuel load did not lead to very sharp differences between the tested fuel loads, although it could be stated that lower fuel loads result in slightly higher emission factors (Lamberg et al. 2011).

At last, the comparison between advanced boilers and advanced combustion stoves learns that generally PM and CO emission factors from advanced boilers are the lowest.

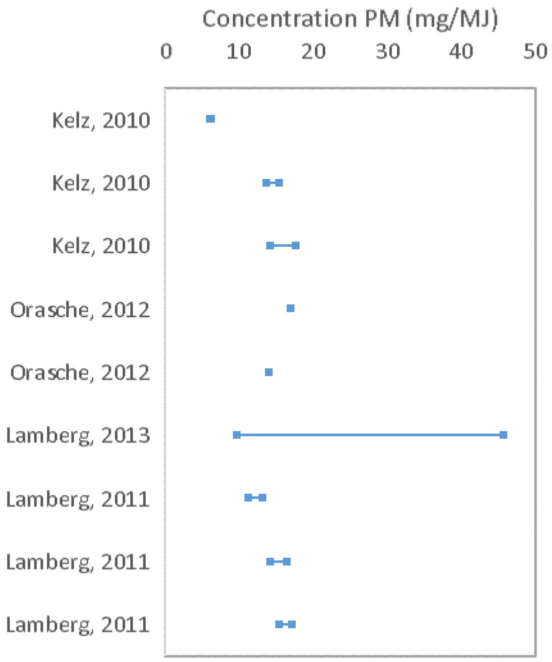


Figure 3-5: Overview of PM emissions of advanced boilers.

Table 3-8: Overview of PM, CO, OGC/PAH and NO_x emission factors of advanced boilers.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP/EEA					100 mg TSP/MJ	2000 mg/MJ	0.010 mg B(a)P/MJ	95 mg/MJ
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Pellets	Real life simulation	6.0-6.2 mg PM_1/MJ	45.4-47.1 mg/MJ	1.7-2.5 mg OGC/MJ 0.006-0.014 mg PAH/MJ	
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Wood chips	Real life simulation	13.6-15.3 mg PM_1/MJ	168.1-182.2 mg/MJ	3.0-5.4 mg OGC/MJ 0.0073-0.0084 mg PAH/MJ	
(Kelz et al. 2010)	PSEUDO REAL LIFE	Manual operation	Logwood	Real life simulation	14.2-17.6 mg PM_1/MJ	700.4-793.1 mg/MJ	62.4-78.7 mg OGC/MJ 0.104-0.105 mg PAH/MJ	
(Orasche et al. 2012)	LAB	Automatic control	SW logs	Normal	17 mg PM_{tot}/MJ	27 mg/MJ	2 mg OCG/MJ 0.00012 mg B(a)P/MJ	143 mg/MJ
(Orasche et al. 2012)	LAB	Automatic control	HW logs	Normal	14 mg PM_{tot}/MJ	15 mg/MJ	1 mg OCG/MJ 0.00012 mg B(a)P/MJ	157 mg/MJ
(Lamberg et al. 2013)	LAB	Automatic control	Pellets	Normal	9.7-45.8 mg PM_1/MJ	94.8-455 mg/MJ	0.76-4.66 mg OGC/MJ	50.2-168 mg/MJ
(Lamberg et al. 2011)	LAB	Automatic control	Pellets	Normal	11.2-13.2 mg PM_1/MJ	7-118 mg/MJ		77.2-84.8 mg/MJ
(Lamberg et al. 2011)	LAB	Automatic control	Pellets	Medium load	14.2-16.4 mg PM_1/MJ	19-245 mg/MJ		69.6-82.4 mg/MJ
(Lamberg et al. 2011)	LAB	Automatic control	Pellets	Low load	15.4-17.2 mg PM_1/MJ	66-280 mg/MJ		72.2-85.8 mg/MJ

Wood/pellet boilers

Emission factors of PM, CO, PAH/OGC and NO_x from wood/pellet boilers are shown in Figure 3-6 and summarised in Table 3-9. When one compares the emission factors of the different listed pollutants with those from EMEP's 'Air pollutant emission inventory guidebook 2016', one can observe that EMEP's emission factor of PM, CO and NO_x lie in the interval of collected emission factor data, while for PAH, the collected emission factors are lower than the one in the EMEP guidebook (see also Table 3-10). As a general trend, one could state that PM, CO and NO_x emissions from the pseudo real life experiments are higher than those from laboratory experiments. A more precise and generally valid correlation between emission factors of both types of experiments could not be found.

The comparison between emission factors of modern pellet stoves and wood/pellet boilers learns that emission factors of both types of devices are in a similar order of magnitude.

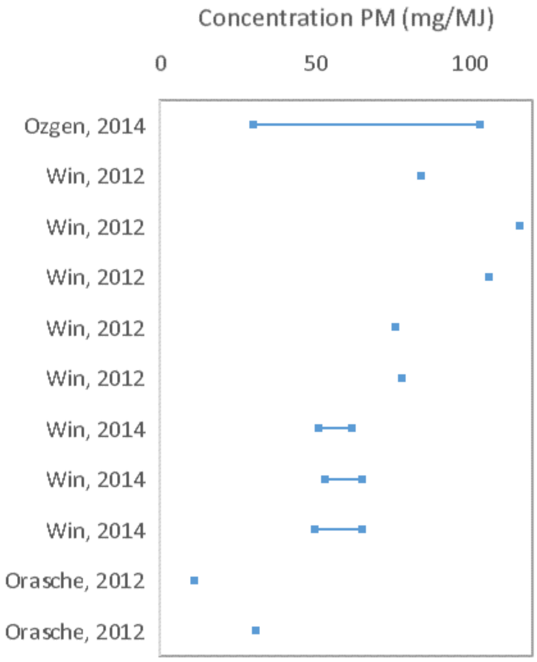


Figure 3-6: Overview of PM emissions of wood/pellet boilers.

Table 3-9: Overview of pellet boiler emissions of PM, CO, OGC/PAH and NO_x emissions.

Author & year	Test conditions	Combustion air supply	Fuel type	Operation	PM	CO	OGC / PAH	NO_x
EMEP / EEA					62 mg TSP/MJ	300 mg/MJ	0.010 mg B(a)P/MJ	80 mg/MJ
(Schmidl et al. 2011)	LAB	Automatic air control	SW pellets	Following EU standard	33.6 mg PM_{10}/Nm^3	190 mg/Nm^3		
(Ozgen et al. 2014)	PSEUDO REAL LIFE	Automatic control	Pellets	Normal operation	30-103 PM_{tot}/MJ	350 mg/MJ	0.00006 mg B(a)P/MJ	71 mg/MJ
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	80 % of nominal power (20 kW)	84 mg $PM_{2.5}$/MJ	547 mg/MJ		64 mg/MJ
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	80 % of nominal power (20 kW)	116 mg $PM_{2.5}$/MJ	393 mg/MJ		63 mg/MJ
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	70 % of nominal power (20 kW)	106 mg $PM_{2.5}$/MJ	271 mg/MJ		61 mg/MJ
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	80 % of nominal power (20 kW)	76 mg $PM_{2.5}$/MJ	197 mg/MJ		93 mg/MJ
(Win, Persson, and Bales 2012)	PSEUDO REAL LIFE	Unknown	Pellets	80 % of nominal power (20 kW)	78 mg $PM_{2.5}$/MJ	236 mg/MJ		95 mg/MJ
(Win and Persson 2014)	LAB	Unknown	SW pellets	High power, medium power & low power	51-62 mg $PM_{2.5}$/MJ	54-485 mg/MJ		62-67 mg/MJ
(Win and Persson 2014)	LAB	Unknown	SW pellets	High power, medium power & low power	53-65 mg $PM_{2.5}$/MJ	12-17 mg/MJ		64-65 mg/MJ
(Win and Persson 2014)	LAB	Unknown	SW pellets	High power, medium power & low power	50-65 mg $PM_{2.5}$/MJ	14-16 mg/MJ		59-62 mg/MJ
(Orasche et al. 2012)	LAB	Automatic control	SW pellets	Normal operation	11 mg PM_{tot}/MJ	17 mg/MJ	2 mg OGC/MJ 0.00003 mg B(a)P/MJ	81 mg/MJ
(Orasche et al. 2012)	LAB	Automatic control	SW chips	Normal operation	31 mg PM_{tot}/MJ	75 mg/MJ	1 mg OGC/MJ 0.00015 mg B(a)P/MJ	127 mg/MJ

Overview

In Figure 3-7, an overview is given of the number of references found for every type based on the different measurement conditions. Based on these results it becomes clear that most data are lab based with only a small fraction being measurements in real-life conditions.

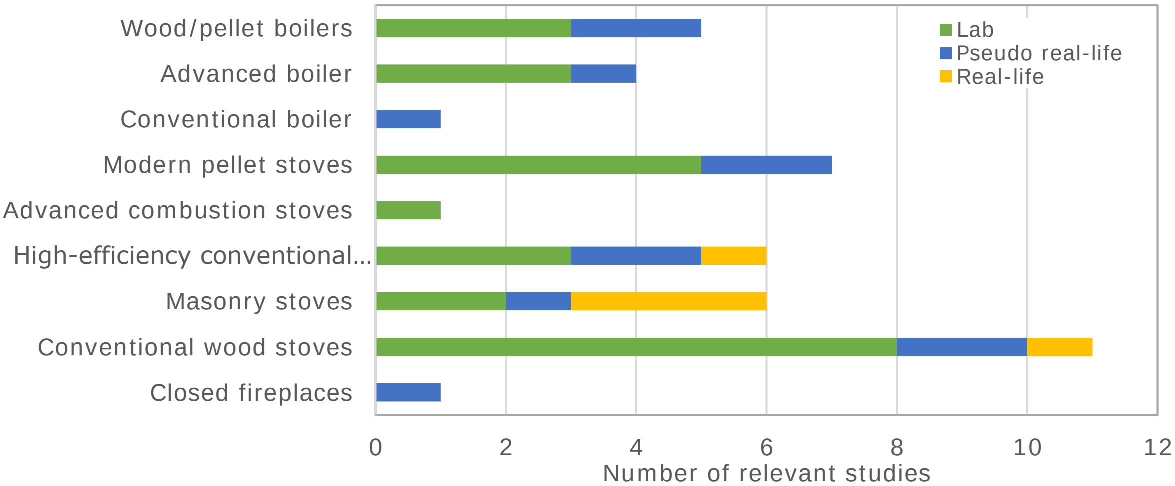


Figure 3-7: An overview of the number of references found per emission measurement condition and per type of appliance.

A summary of the data mentioned above is given in Figure 3-8 containing a boxplot of all available data points using the unit mg/MJ. From this overview, it is clear that newer types of wood combustion appliances generally have lower emissions. This information is also confirmed in Table 3-10 which contains the EMEP's 'Air pollutant emission inventory guidebook 2016' values and the minimum and maximum values as found from Table 3-1 to Table 3-9. It is important to note that there are exceptions to the general finding and that sometimes higher emissions are reported for newer stoves types than for certain older types. This is probably due to the operating conditions in the test which, as will be shown further in this report, can have a large impact on the emissions.

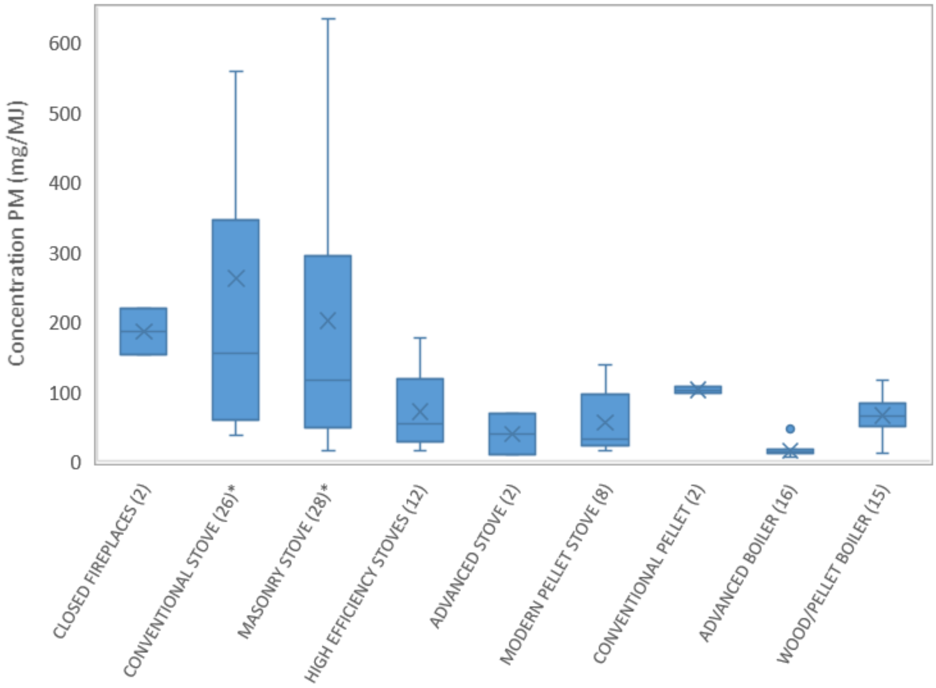


Figure 3-8: Boxplot summary of all data points (number given between brackets) for each type of wood combustion appliance. *category containing outliers above 1000 mg/MJ.

Table 3-10: Overview of emissions data collected from all different types of wood appliances with unit mg/MJ.

	PM (mg/MJ)		CO (mg/MJ)		PAH (mg/MJ)		NO_x (mg/MJ)	
	EEA (TSP)	Literature	EEA	Literature	EEA (B(a)P)	Literature	EEA (TSP)	Literature
Closed fireplace	800	152-219	4000	3949-5030	0.121	0.014	50	105-140
Conventional wood stove	800	38 - 955	4000	1100-7200	0.121	0.0325-220	50	35 - 66
Masonry stove	800	16 - 833	4000	703-10611	0.121	0.081-14.10	50	72 - 83
High efficiency stove	400	15 - 176	4000	100-7829	0.121	0.0003-340	80	99-182
Advanced stove	100	9.7-68.05	2000	731-824	0.010	NO DATA	95	NO DATA
Modern pellet stove	62	16 – 139	300	73-413	0.010	0.000077-0.5	80	32-165
Conventional boiler	500	98.6-106.1	4000	8969-12 632	0.121	3.39-18.85	80	NO DATA
Advanced boiler	100	6.0-45.8	2000	7-793.1	0.010	0.00012-0.105	95	50.2-168
Wood/pellet boiler	62	11-116	300	12-547	0.010	0.00003-0.00015	80	59-127

4. Strategies for emission reduction

Two strategies are possible to reduce emissions namely source control and end-of-pipe solutions. Most end-of-pipe measures for residential wood combustion are based on industrially available techniques. In those applications high removal efficiencies of emissions can be obtained (VITO 2017). In order to reach these removal efficiencies, it is important that process conditions remain constant and are constantly followed up. In residential wood combustion these aspects are much harder to achieve, since they are often based on the quality of the wood, the installation of the chimney and the stove, maintenance and the end user. As a consequence it is important to check the real emission reduction reached with these techniques in comparison with the theoretically achievable reduction.

4.1. Source control

In this report the effects of source control measures are included in the typology of the different stoves. Overall the following technologies are integrated inside the newest appliances.

- Air supply strategies: For an optimal combustion, air supply is crucial. Both excessive air and a shortage of air can create an inefficient combustion with a lot of emissions. An important aspect to improve emission characteristics of wood combustion devices is based on the concept of air staging. It means that the air supply is split into two flows; one directly into the primary combustion chamber and the second one above the primary combustion zone. In air staging, the first flow is kept low so that the fuel just continues to burn while the second flow is present to completely oxidise the gaseous compounds (T. Brunner, Obernberger, and Scharler 2009).

- Fuel feeding concepts: Using an automatic system for feeding the fuel to the combustion chamber will ensure the correct load of wood. These system are especially useful and convenient when pellets are the fuel. Using such a system, the correct amount of fuel can be delivered and overloading can be eliminated. In wood log combustion devices, fuel feeding can be optimised through design of the combustion chamber or by indicating the user when to add fuel to the fire (T. Brunner, Obernberger, and Scharler 2009).

- Combustion chamber and air supply design: Designing the combustion chamber proofs to be a key element in reducing pollutant emissions. Innovation lies in the geometries as well as the air injection used inside the combustion chamber. Simulation with computational fluid dynamics can help significantly during the development phase to eliminate death zones and optimise the combustion (T. Brunner, Obernberger, and Scharler 2009).

- Process control concepts: A smart system is focused on ensuring that the right temperature and air flow is present in the combustion chamber. This can be achieved by automatically regulating the air intake to optimise the burning process (Illerup et al. 2014).

4.2. Electrostatic Precipitator

An electrostatic precipitator (ESP) is a typical instrument to remove all sizes of particulate matter as long as the pollutant can be electrically charged. Organic compounds, NO_x and CO are typically not removed, which is why literature often does not mention them.

Mechanism

In ESPs a high voltage is applied between two electrodes, a discharge electrode and a grounded electrode. Due to this high voltage, ionisation of the gas and mainly particulate pollutants present in the gas occurs. As a consequence of the electrical field between the electrodes, charged pollutants are attracted to the grounded electrode and deposit onto it. As a result, particulate pollutants are removed from the gas stream.

Lab performance

In the IEA report of Task 32, 12 different ESP systems available on the market were considered and tested, most of the time under lab conditions (Obernberger and Mandl 2011). The focus of ESP lies in the reduction of TSP, but in some cases PM_1 is also taken into consideration.

Two different concepts are present in the mentioned IEA report. The first one are ESP models that can be used as a retrofit on top of the chimney and the others are placed between stove and chimney to ensure an early removal of TSP. Both concepts have their merits, but during design several aspects need to be considered, e.g. flue gas temperature or robustness.

In Table 4-1 the available removal efficiencies for TSP are given based on the value measured under laboratory conditions. If available, the value for removal efficiencies of PM_1 are also presented. When real-life tests were conducted, these data were also added (columns containing label real-life). Important to take into account is that the tests conducted in these studies are performed by different laboratories. This results in different protocols that are used and data that is presented in different fashions. The values presented here are a compilation of these data. Table 4-1 clearly shows that the removal efficiency of ESPs ranges from 11 to 99%. This wide range is due to several issues which should be taken into account:

- Type and age of stove
- Temperature of the flue gasses
- Fuel
- Ignition procedure
- Maintenance of the ESP

Table 4-1: Overview of removal efficiency based on the IEA report of Task 32. Most tests are conducted under laboratory conditions. Where available, real-life tests were included.

Device	Test TSP	Real-life TSP	Test PM_1	Real-life PM_1
Type A	No data		97.50%	
Type B	11-17%	41%		53%
Type C	26-94%			
Type D	60-80%			
Type E	68-78%		71-83%	
Type F	69%			
Type G	>70%	68%		60%
Type H	>70%			
Type I	82%			
Type J	85-99%	54-61%		
Type K	87%			
Type L	<93%			

It is also shown that in two of the three cases the real-life values are slightly below the results measured under laboratory conditions. In one case, the real-life test was significantly better than the laboratory test result, but in that case the measurements were conducted in two different labs, using different appliances and test methods. This clearly indicates difficulties in comparing emission reduction techniques (Obernberger and Mandl 2011).

Around the same time the Danish Ministry ordered a study to compare 5 different ESP technologies. These were all tested under laboratory conditions and in real-life. In both operation conditions an old stove (sold between 1990 and 2007), an eco-labelled stove (building year unknown, still on the market in 2012-2013) and a boiler were used. The results showed a reduction in $PM_{2.5}$ emissions during the test in the lab but removal efficiencies were rather low. Using the eco-labelled stove, which is a more recent appliance, the tests resulted in similar or lower emissions than when ESP systems were introduced on older appliances. Additionally, implementation was challenging due to several operational constraints and side effects (Schleicher et al. 2011).

Real-life performance

More recent a 2-year study under real-life conditions was executed by Brunner et al. using a specific ESP system (Oekotube). This system was selected because of its potential to be used in older biomass burning appliances. The year of manufacture of the used wood combustion appliances were 2010 (logwood boiler), 1997 (logwood boiler) and 2009 (logwood stove) (Thomas Brunner, Wuercher, and Obernberger 2017).

The results of this study are shown in Table 4-2. While reduction efficiency is rather high, the ESP is not able to reduce the effective concentration of TSP below the European eco-design legislation on a permanent base.

Table 4-2: Achieved removal efficiencies for TSP and PM_1 and effective TSP concentration in the flue gas for the different tested wood combustion devices (Thomas Brunner, Wuercher, and Obernberger 2017).

	2010 boiler	1997 boiler	2009 stove
TSP removal efficiency [%]	30-93	35-83	57-93
PM_1 removal efficiency [%]	55-96	44-93	50-97
Concentration TSP after ESP [mg/Nm³]	4-174	22-154	14-46

Risks and disadvantages

The data above show that under the right conditions ESPs can realise significant reductions in PM emissions. Nonetheless, several risks and issues are described in literature related with this technology. These are listed below (Obernberger and Mandl 2011; Schleicher et al. 2011):

- Sparkover effects: one of the risks of ESP is sparkover in the reactor. Sparkover can occur due to the higher temperature present in the ESP where electrons are moving directly between electrode and collector. When this occurs frequently, a reduction in power or a shutdown of the ESP is needed and the effectiveness of the system decreases.
- Noise: typically associated with sparkover is a certain sound, which can be annoying.
- Temperature effect on the electrode: in some cases the electrode can deteriorate under influence of the higher temperature of the flue gas and thereby thus significantly reduce the removal efficiency.
- TSP deposition on the collector electrode: by collecting the TSP on the electrodes the effect of the charging and attraction towards the collector is reduced, resulting in lower efficiencies. Another possible side effect is the re-entrainment of the particles in the air, especially with agglomerated particles this is possible due to their lower resistivity.
- Price: most technologies available on the market are relative expensive, especially compared with the overall cost of a wood combustion device.
- Resistivity and toxicity: particles going through an ESP should have the right resistivity. In cases where this is too high or too low, the attraction of the particle on the collector electrode decreases and low efficiencies are achieved.

A possible solution to overcome some of the described drawbacks, is the introduction of novel technologies based on ESP such as plasma catalysis. In such technologies the collector electrode is treated with a photocatalytic coating making degradation of the deposited pollutants on the electrode possible. Another effect is that the plasma results in radical formation in the reactor. These radicals are capable of reducing the concentration of OGC and NO_x (Van Wesenbeeck, Hauchecorne, and Lenaerts 2017).

4.3. Catalytic converter

The use and integration of catalytic converters in wood stoves in Europe is rather limited. In recent years, most new developments of European wood stove manufactures focused on the optimisation of the primary combustion process (Reichert, Schmidl, et al. 2017). In Northern America the focus lies more on the active integration of catalytic converters in wood stoves (15% of the approved stoves contains a catalytic converter) (US EPA 2015). Most available data is thus related towards that market (US EPA 2015; Kaivosoja et al. 2012).

Mechanism

The principle behind a catalytic converter is that it decreases the temperature needed to oxidize pollutants to achieve complete mineralisation. To achieve this, a catalyst, often a noble metal like platina or palladium, is coated onto a honeycomb structure which can be ceramic or metallic. This is placed inside the combustion chamber or inside the chimney. Especially for volatile organic compounds, CO and NO_x this method has already proven it effectiveness in other applications, e.g. as the three-way-catalyst in cars or in large scale facilities (Hukkanen et al. 2012).

Performance

A limited amount of literature is available with regards to reduction efficiencies of exhaust emissions by catalytic converters.

The IEA report of 2011 describes two commercially available systems. The first system reports efficiencies up to 85% for reduction of TSP according to the manufacturer, but no independent tests are available. Another commercial catalytic converter claims to achieve a reduction of 35% for TSP, up to 75% for hydrocarbons, up to 82% for CO and up to 95% for soot. The Graz University of Technology performed real-life tests with these appliances and obtained the following results: 0-14% reduction of CO, 0-15% reduction of hydrocarbons and increased PM_1 emissions due to poor combustion behaviour of the stove (Obernberger and Mandl 2011).

A similar conclusion about catalytic converters is found by Kaivosoja et al. where a limited reduction is achieved for CO (around 25%), hydrocarbons and PAH while highly toxic PCDD/F by-products are formed (Kaivosoja et al. 2012).

More recent literature nonetheless shows significant improvement in the pollutant removal potential of catalytic converters. This can be attributed to an increased knowledge of the catalyst itself but also to an improvement in stove design with integrated catalytic converters. For example, the research of Reichert and co-workers reported that conversions of 95% for CO, 60% for OGC and 30% for PM could be achieved using a catalytic converter. Beside these high conversion rates, quick responses were observed due to the elevated temperature at which the catalyst was operated. Important in this research was the type of catalyst used. The metallic honeycomb has a higher conversion rate than the ceramic one, which demonstrates the importance of the type of catalyst used. The experiments were performed under pseudo real-life conditions that are highly relevant for real-life operation (Reichert et al. 2018).

Similar conclusions are reported by Wöhler and co-workers. Their experiments were conducted under pseudo real-life conditions using an advanced stove built in 2016 with air staging and separate control of primary and secondary air. The stove was originally equipped with a ceramic filter but for the test it was replaced with a ceramic catalytic filter and a dummy to keep the same operational conditions during the experiments. The test conducted with the ceramic filter shows limited reductions, while the use of the metallic honeycomb structure gives similar results as reported by Reichert et al. when tested under nominal load. During start-up phase, lower reductions are achieved, illustrating the importance to focus on this phase in experiments (Wöhler et al. 2017).

All tests mentioned above are conducted in short time periods with fresh catalysts. In order to study the stability and reliability of the catalyst, longer tests should be performed. As we know, catalysts regularly need to be re-activated by burning off all deposits. The optimal window of operation and the long term performance of the catalyst require further study (Reichert, Schmidl, et al. 2017).

Risks and disadvantages

Similar to ESP, a positive effect regarding pollutant emission reduction by using a catalyst can be observed. Nonetheless, several risks are found when using a catalytic converter:

- During start-up and end phase the temperature inside the catalyst can be too low to obtain an optimal oxidation (Ozil et al. 2009; Carnö, Berg, and Järås 1996; Hukkanen et al. 2012).
- Due to poisoning, thermal deactivation and fouling deactivation of the catalyst can occur (Ozil et al. 2009; Carnö, Berg, and Järås 1996).
- Information about the impact on particle reduction is limited (Hukkanen et al. 2012).
- Creation of highly toxic compounds such as PCDD/F (Kaivosoja et al. 2012) could be problematic and needs to be further investigated.

4.4. Ceramic filters

Integrating a purely ceramic filter without catalytic activity is rarely found in literature. When present, the reduction rates were rather low or non-existent, illustrating the limited potential of this technique (Obernberger and Mandl 2011; Wöhler et al. 2017). The reason for the limited testing is related to the fact that in most cases such a filter is directly incorporated in the design of the wood combustion device. By removing it from the stove, combustion is altered, which makes comparison very difficult. However, pollutant emissions are very similar to comparable stoves without a ceramic filter (Obernberger and Mandl 2011).

5. Impact of emissions on the atmospheric concentration

Knowledge about emissions associated with residential wood combustion with or without emission reduction technologies is important, but the ultimate goal should be the determination of their effect on the overall air quality. Besides pollutants that are formed during the combustion, also secondary pollutants can be formed from precursors emitted by residential wood combustion.

5.1. Secondary Organic Aerosol Formation

Current Belgian legislation focuses on CO and PM concentrations measured at the exit of a chimney. In European eco-design legislation organic gaseous carbon (OGC) and NO_x concentrations measured at the exit of the chimney are also included. Secondary pollution formation in the atmosphere is not taken into account. Recent literature shows nonetheless that there is large potential for the formation of secondary organic aerosol (SOA) (Denier Van Der Gon et al. 2015; Vicente and Alves 2018).

The origin of these SOA lies in the incomplete combustion and the formation of condensable organic compounds (COC) and volatile organic compounds (VOC). In Figure 5-1 an overview by Nussbaumer on the formation of organic aerosols and other products is presented (Nussbaumer 2017). The COC and VOC fraction and their potential to form SOA are important topics for further research (Vicente and Alves 2018; Keller and Burtscher 2017; Bruns et al. 2016). The lack of in depth knowledge on the faith of this fraction is also an important object of study giving its effects on the environment and human health (Vicente and Alves 2018).

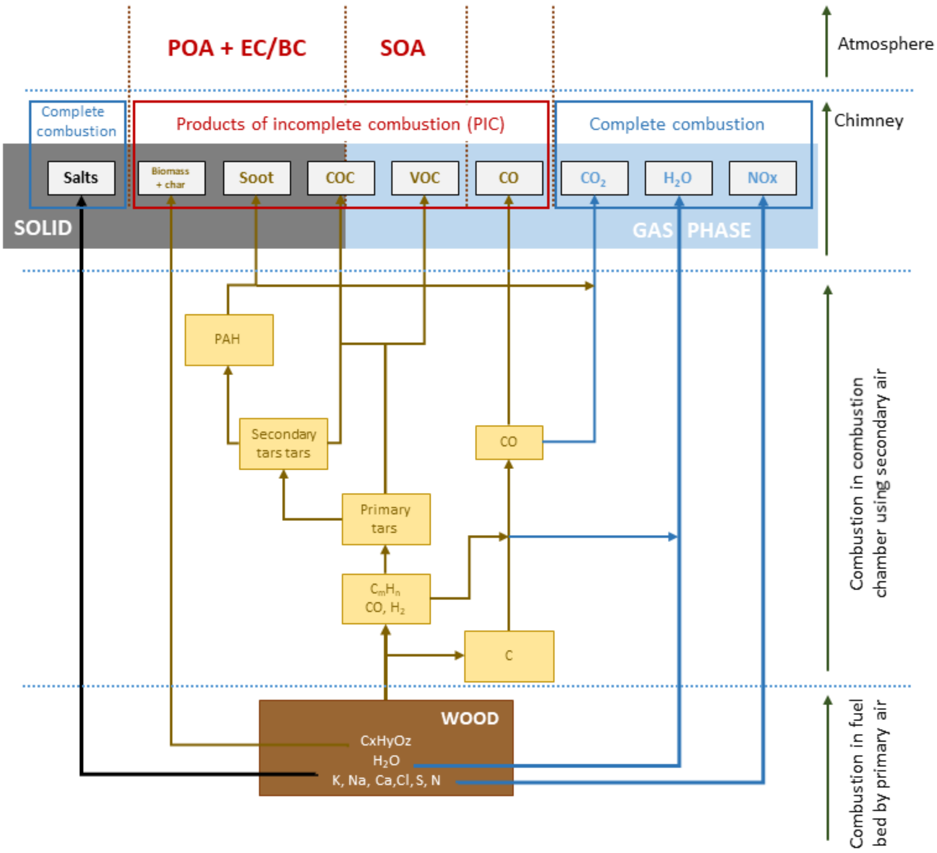


Figure 5-1: Overview of the burning process of wood combustion focused on PM10. Adapted after (Nussbaumer 2017).

In one of the studies by Keller and co-workers a micro smog chamber (MSC) is used to simulate SOA formation. He describes a lab experiment with several different small wood stoves and pellet stoves, as well as real-life tests. The real-life tests were executed with medium sized boilers for heating warm water at nominal power during the winter of 2011/2012. The results of this study show that when using small combustion installations fired with log wood, concentrations of 53 mg/m³ SOA potential could be observed during the start phase and 8.8 mg/m³ during stable operation. For pellets, these values were 42 mg/m³ and 1.6 mg/m³, respectively. Especially in the start-up phase the observed concentrations are at the level of current PM_{10} legislation thresholds (Keller and Burtscher 2017).

Precursors

The importance of SOAs in the overall exhaust emission confirms the need for further investigation. Because this subject has proven to be very complex, it might be better to focus on the precursors that are responsible for the formation of SOA (Keller and Burtscher 2017). Research by Grieshop has evidence that 85% of all SOA are related to low volatile species (Grieshop et al. 2009). This is further specified by Bruns, who identified 22 precursor molecules for SOA formation, with phenol, naphthalene and benzene being the three most important ones (Bruns et al. 2016).

Mitigation strategy

A well-known technology for removal of particles in flue gas cleaning is the use of ESP. As described earlier, the removal efficiency for other pollutants than PM is rather low, including the precursors of SOAs. A possible solution might be the removal of the least volatile OGC molecules. This can be achieved by a gas cooling in front of the ESP in order to condensate the least volatile OGCs into particles.

Keller and co-workers studied a system currently available on the market, under the name NOSMOG, using a logwood stove equipped with a cool down system. Results showed that the SOA potential dropped significantly by combining the ESP with a cooling system. This illustrates the potential of flue gas condensing to remove SOA precursors and thus reduce the SOA formation (Keller and Burtscher 2017).

5.2. Real-life implementations on a larger scale

Small estate

A study for the Danish Ministry of the Environment has been executed in a town called Hillerød, in a small estate called Slåenbækken. In this estate, consisting of 20 houses, 7 wood stoves were present that were regularly used during winter period. Data was collected both inside the estate as 27 km away in a background measurement station.

During the measurement campaign no clear impact on the outdoor concentrations could be observed when wood combustion devices were equipped with end-of-pipe technology. A reason for this could not be identified and further research is needed (Schleicher et al. 2011).

City scale

To investigate the impact on air pollution on a larger scale, two other studies have been done on city scale. In the first study a change-out program was used, while in the second case *end-of-pipe* solutions were implemented on wood combustion devices.

The change-out program was done in 2005-2007, so the appliances used are currently no longer state of the art. This should be taken into account when interpreting the results. The overall effect was that a reduction of 20 to 28% could be achieved by the changeout at that time (Ward, Palmer, and Noonan 2010).

In a more recent study executed in Australia a catalytic converter as end-of-pipe technology was implemented in existing wood combustion devices. A comparison between the concentrations in ambient air was done for four towns that are similar in topographical and population size and in the number of wood stoves. In one of them, people were asked to use a commercially available catalyst free of charge inside their stove. Although 80% of them accepted the offer, no significant reduction could be observed in the emissions of $PM_{2.5}$ in the atmosphere, while under laboratory conditions a reduction could be observed. Possible explanations for the observations are meteorological reasons and changes in background concentrations, but further investigation is still needed. This should include the effect the community can have on the use and therefore effectiveness of the catalyst (Johnston et al. 2016).

6. Knowledge gaps & future research needs

The literature review identified several important knowledge gaps. An overview is given below. A brief overview of the research needs to address the knowledge gaps is described as well.

6.1. Lack of data under real-life conditions

Based on the information provided in Chapter 4, it becomes clear that there is a lack of data measured under real-life conditions, i.e. measured at the premises where wood combustion appliances are used in-house. The vast majority of data has been collected under standardised test conditions. Some studies demonstrate the effects of combustion practices on emissions under controlled test conditions, e.g. by using various wood types. Real-life conditions are rarely tested, and the methods used are insufficiently detailed in literature. The use of different methods makes it difficult to find a correlation between data from different types of measurements (Vicente and Alves 2018).

Besides this, it is also observed that most literature refers to older appliances. Indications on the performance of modern stoves and boilers are scarce. A first characterisation of the important elements of real-life testing is elaborated in Chapter 7.

6.2. Comparison of data is challenging

When studying the literature there is a clear lack of consistency in the use of units for describing emissions of wood combustion. This creates an obstacle to objectively compare data between different experiments and stoves.

In Table 6-1 an overview is presented of the different units found in literature. In general, the units can be divided into two types: energy and air volume related units. The energy related units express emissions per amount of released heat or per mass of wood combusted. Emissions shown in air volume related units are expressed per volume of combustion air, which depends on the characteristics of the stove. As a result, air volume related units hamper comparison between different wood combustion devices. Nonetheless, the unit mg/Nm^3 is used in standard tests.

Table 6-1: Overview of units for emitted pollutant concentrations from wood combustion devices used in scientific literature.

Energy related	Air volume related
g/kg_{dry_wood}	mg/Nm^3
g/GJ	mg/Nm^3 in STP 13% O_2
g/u	ppm
	vol%

A realistic conversion between energy and air volume should be made to compare data on a same unit base.
Skreiberg describes a methodology to convert between the different units of emissions. An overview of these conversions is presented in Table 6-2. A number of conversions are relative easy to make, but for the conversion of MJ to Nm^3, knowledge about the volume of flue gas is needed (Skreiberg 2002).

Table 6-2: Table containing conversion calculation based on (Skreiberg 2002).

To / From	E1 mg/Nm³ at O_2	E2 mg/Nm³ at 13% O_2	E3 mg/kg	E4 mg/MJ
E1 mg/Nm³ at O_2	E1	$E1.\frac{V_{FG}}{V_{FG\_13\%}}$	$E1.V_{FG}$	$E1.\frac{V_{FG}}{UHV}$
E2 mg/Nm³ at 13% O_2	$E2.\frac{V_{FG\_13\%}}{V_{FG}}$	E2	$E2.V_{FG\_13\%}$	$E2.\frac{V_{FG\_13\%}}{UHV}$
E3 mg/kg	$\frac{E3}{V_{FG}}$	$\frac{E3}{V_{FG\_13\%}}$	E3	$\frac{E3}{UHV}$
E4 mg/MJ	$E4.\frac{UHV}{V_{FG}}$	$E2.\frac{UHV}{V_{FG\_13\%}}$	$E4.UHV$	E4

with
V_{FG} = Nm³ dry flue gas per kg dry fuel
$V_{FG_{13}\%}$ = Nm³ dry flue gas per kg dry fuel based on STP of 13% O_2
UHV = Upper heating value = the amount of energy you have per kg dry fuel (MJ/kg)

To convert mg/Nm³ to mg/MJ the type of fuel should be known to determine the UHV. The heating values that are used range between 15.6 and 19.25 MJ/kg. In the EMEP/EEA air pollutant emission inventory guidebook it is suggested to use 18 MJ/kg for wood logs and 19 MJ/kg for wood pellets in case no details are provided about the fuel. Additionally the volume of dry flue gas of the used stove should be known. This last number cannot be determined based on stoichiometric values because an excessive amount or air is typically used. During measurements, it is therefore important to include this parameter in the monitoring (Skreiberg 2002).

A special program, called FuelSim – Average, is developed that can be used to do the conversion. With the program it is possible to follow the mass, volume and energy balance of a continuous combustion process (Skreiberg 2002).

6.3. Effective impact on air quality

As shown in Chapter 5, the direct impact of emissions from residential wood combustion on the air quality is not completely clear. One of the important aspects in this regard is the lack of knowledge about the SOAs potential due to residential wood combustion. Uncertainty remains about the exact formation pathway of SOAs, which precursors are responsible for their formation and how high the ambient contribution can become. Further studies are needed that are focussed on the formation of SOA.

Directly related to this problem is the limited knowledge on the impact of different emission reducing strategies on local air quality. This type of studies proofs to be very difficult due to several external factors like long range transport, topography, weather and atmospheric stability. Comparison of different results is therefore difficult, making it hard to know the effective potential of the different approaches to reduce primary emissions and the formation of secondary organic aerosols.

7. Towards characterisation of real-life conditions

The results of Chapter 3 confirm that a clear difference between real-life and lab emissions exists. Therefore, while studying exhaust emissions from wood combustion appliances, five different elements will influence the final results. These are the following:

- Technological factors
- Test-related factors
- Operating conditions – non-user behaviour
- User behaviour
- Fuel

Technological factors

Chapter 3 illustrates the impact of technology on exhaust emission levels. First, a clear difference between traditional wood log stoves and pellets stoves is observed. Furthermore, the level of technology implemented with the stove is of upmost importance. The implementation of technologies like air staging, optimising the dimensioning of the combustion chamber or improving the air tightness of the combustion chamber significantly reduces exhaust emissions (Reichert et al. 2016) and also influences the difference between lab and real-life conditions.

From the earlier results, it can be concluded that more recent appliances perform better regarding pollutant emissions, but around 80% of appliances in Belgium is older than 2010 (Agoria-CIV 2017). As a result, the majority of the wood combustion devices currently installed in Belgium is not equipped with state-of-the-art technology. A potential solution might be the retrofit of emissions abatement technologies under strictly controlled conditions (Obernberger and Mandl 2011).

Test-related factors

As described, three different types of tests are performed on stoves. In current legislation the standard lab test employs optimal steady-state situations resulting in limited variability of optimal burning performance. In practice, testing needs to be performed in more realistic cycles, similar to the more realistic testing cycles for determination of exhaust emission by cars. Of course, real-life testing with realistic conditions is the best solution (Reichert et al. 2016).

Operating conditions – non-user behaviour

Operating conditions are typically divided into two distinct categories based on the possibility of user interference: user behaviour and non-user, operating conditions. The non-user operating conditions are related to flow conditions induced by natural draught (Reichert et al. 2016).

Reichert and co-workers investigated the impact of draught. They observed that the effect of draught depends on wood combustion device and that draught can influence emissions in either positive or negative way. Around the typical draught under real-life conditions (20-30 Pa), small differences were observed. Still, an effect on concentration is present since draught affects combustion efficiency. Higher draught leads to lower efficiency and thus a longer heating period that increases exhaust emissions (Reichert, Hartmann, et al. 2017).

User behaviour

User behaviour factors highly influence real life emissions, since they have a direct impact on operating conditions. One of the most important variables is fuel properties, which is described in the next section. Other influences are:

- Ignition method: in wood combustion there are typically two strategies to ignite the fire: top-down or bottom-up. In the first case the firewood is placed below, smaller material is placed above and the ignition aid is placed on the top. The fire thus starts on top and needs to migrate downwards. In a bottom-up strategy, the starting aid is placed on the bottom of the wood combustion device and firewood is placed on top of it. Described by Hartmann in 2012 and Reichert in 2016, the top-down method results in significantly lower emissions of PM, OGC and CO when compared with the bottom-up method (Hartmann et al. 2012; Reichert et al. 2016). More recent reports were less conclusive in relation to the ignition method. No clear results could be found using the different wood combustion devices studied, making the impact of the ignition method less clear (Reichert, Hartmann, et al. 2017).

- Air settings: another important aspect is the air-to-fuel ratio. While modern appliances are mostly equipped with automatic air control, it is more common to manually control the air flow. Fachinger and co-workers found that by using small and very dry logwood with excessive air, emissions could significantly rise (up to six-fold) due to reduced residence time (Fachinger et al. 2017). On the other hand, a limited amount of air results in a smouldering phase, something that typically occurs at the end phase of a burning cycle and shows significant increase in emissions of all pollutants (Tissari et al. 2008; Schmidl et al. 2011; Reichert et al. 2016).

- Maintenance: it is important to have regular maintenance of the appliance to keep it functioning as optimal as possible. Effects like soot deposition or air leakages will have a direct negative impact on the emissions. Especially the impact of air leakage by damaged door gaskets and air-tightness will have significant negative impact on the emissions of TSP (Sevault et al. 2015).

Fuel

One of the most important user behaviour factors affecting emissions is the fuel that is used. From literature it is clear that the use of fuels other than solid wood, briquettes or pellets has a significant negative influence on the emissions. This is especially the case if treated wood with paint, paper or cardboard is used (Fachinger et al. 2017).

But even when only solid wood is considered as fuel, significant differences in emissions using the same appliance can be observed. The impact of fuel type is one of the most studied topics under real-life conditions. However, different studies are difficult to compare due to the difference in measuring methods, stoves and settings used. In what follows, a general overview of the important aspects is presented:

- Type of wood: an important factor in the emissions is the kind of wood used. In most cases this is divided into two groups being hardwood and softwood. Different studies lead to different conclusions. Both Calvo and Gonçalves have found that softwood is better than hardwood (Calvo et al. 2014; Gonçalves et al. 2010). Hartmann on the other hand showed that the use of hardwood is preferential and recommended (Hartmann et al. 2012). The results in the overview in Chapter 3 confirm these mixed results.

- Moisture content: different studies compared pollutant emissions between high (moisture content > 20%) and moderate moisture contents (between 10 and 20%). From these studies it can be concluded that emissions of PM and PAHs are higher when the moisture content of the fuel is higher (Shen et al. 2013; Hays et al. 2003; Fernandes et al. 2011; Orasche et al. 2013; Mcdonald et al. 2000). One report states that the optimal firewood moisture content ranges between 7.5 and 20% (Hartmann 2012). Although not much research has focused on pollutant emissions from firewood with moisture contents lower than 7.5%, one study shows that PAH emissions are higher when very dry wood (moisture content = 1.6%) is used instead of moderately dry wood (Orasche et al. 2013).

- Fuel refilling: refilling a wood combustion device during operation can result in significant negative effects on pollutant emissions when this is badly timed. Surveys with real-life users however learned that mostly refilling occurs at the right moment. Most users recharge wood at the moment the flames are almost extinguished, the moment that is actually the most optimal one to ensure limited emissions. A second aspect related to fuel refilling is the amount of fuel that is added. Based on surveys this is often not optimal and people tend to overload their stove, which results in decreased burning efficiency and increased emissions (Reichert et al. 2016).

- Quality of the fuel: even when regulated pellets are used, significant differences in emissions are observed. Venturini and co-workers investigated three different types of pellets based on the ISO 17225-2 technical standard: pellets from the highest class (A1), pellets from the lowest class (B) and pellets that do not comply with the legislation. The results showed that lower quality pellets resulted in increased TSP emissions two to five times (Venturini et al. 2018).

A big problem with all the described factors is that consistent information of typical or average real user behaviour is lacking. As a result, assumptions currently made in scientific literature on (pseudo) real life emissions can proof to be completely different in reality. A better understanding of these aspects is required. This can be done by performing surveys with real-life users in order to gain knowledge about their operation of a stove (Wöhler et al. 2016; Reichert et al. 2016). Another problem is that a small fraction of real users (e.g. people burning wet, contaminated wood in old stoves) could have a relative high contribution to the total emissions. Therefor good knowledge of best, average and worst case scenarios and their occurrence is essential to estimate the total real-life emissions.

8. Policy Advice

After the findings of the literature review, the following policy recommendations are proposed to better control the emissions from wood combustion under real-life conditions. The recommendations are grouped under the following key messages:

- Better understand the use of wood stoves in practice, and the impact on regional air quality
- Develop test protocols to monitor emissions under real-life conditions, while ensuring data comparability
- Develop a governmental strategy for reducing and better controlling residential wood smoke
- Online tool to guide potential buyers, users, retailers and vendors to the cleanest stoves and good practices in using them

1. Better understand the use of wood stoves in practice, and the impact on regional air quality

At the moment, there is no exact knowledge of the number and the types of stoves in active operation. Questions that are to be answered include: 'Is wood burning mostly relevant in rural areas, or also in urban areas? How often are stoves used in practice? Which burning practices and wood type do users have? To which extent are the emissions measured under test conditions valid for an assessment of the cumulative impact of wood burning on local and regional scale?'

A survey could be undertaken to approximate the number of households that use wood burning. Statistics from vendors and/or retailers could potentially be of use to cross-check the survey results. Additional data that can be collected in the survey are a breakdown on the type of stoves used, burning practices and fuel type and quality. A broader survey can also be undertaken to better understand the knowledge of citizens on the adverse effects of wood burning to the environment and human health and on the nuisance stove users create to neighbours.

2. Develop test protocols to monitor emissions under real-life conditions, while ensuring data comparability

The lack of data on emissions under real-life operation, and the challenges to data comparability are important barriers found in this study. To better understand the real-life emissions from wood burning appliances, a set of test protocols can be developed to systematically monitor real-life and pseudo real-life conditions, preferentially at European level. A separate testing protocol is to be developed for wood log appliances and pellet appliances. Under pseudo real-life conditions, the emissions from a range of burning practices, including best, average and worst case scenarios, can be monitored under controlled conditions. To enable the comparison of inherently heterogeneous burning practices under real-life conditions, protocols need to be developed that consider the various technologies of which a stove/boiler is composed, user behaviour (e.g. ignition method, air settings, maintenance) and fuel types (e.g. wood species, moisture content of wood, fuel amount and sequence of loading).

3. Develop a strategy for reducing and better controlling residential wood smoke

In addition to the general air quality strategy for Flanders (under development), a specific strategy can be developed to reduce residential wood smoke. The strategy can hold actions for the regional and local government, vendors, retailers and users. Specific actions need to be tailored to households having older wood stoves compared to household owning more recent stoves. The strategy can be composed of specific actions, for which a fact sheet can be developed, explaining potential impacts, time schedules, transitional arrangements, budgetary aspects etc.

Potential actions that can be included in a strategy to reduce residential wood smoke can include hard/compulsory measures such as changeout campaign for older stoves/boilers, compulsory maintenance of stoves/boilers, burn bans on days with bad air quality and softer measures aiming to change behaviour, such as information campaigns on best practices for users, vendors and retailers.

Compulsory actions can be useful for actions that users, retailors or vendors would not accept without a binding government decision and/or legislation. A disadvantage of compulsory action is that the setting up of compulsory actions could take more time and may generate resistance from the general public. Voluntary actions and information actions might engage stakeholders more efficiently. A combination of compulsory and voluntary measures can also be considered.

A phase-out campaign of stoves/boilers could be a potential action. Older, low performing stoves could be banned and/or be replaced by newer, cleaner devices. To decide which stoves would need to be phased out, thresholds values can be setup, based on e.g. age or real-life emissions. A phase-out campaign can speed up the retirement of older appliances. Yet, substantial logistical effort is needed to firstly identify low performing stoves and secondly achieve replacement or removal. In analogy with the energy certificate, house owners could be obliged to obtain a certificate on their appliance when the property is sold. Another strategy might be the obliged registration of each newly bought wood combustion device, e.g. in the existing home pass. An advantage of registration is that step by step an overview of the different devices in use can be set up. Beside the registration of new devices, a registration process for all currently used devices could be considered, as is already done in Montreal. Furthermore, obligatory maintenance of appliances can also be considered, potentially associated with an assessment on the emissions.

4. Online tool to guide potential buyers, users, retailers and vendors to the cleanest stoves and good practices in using them

Informative and educational material can be developed on the best wood burning practices to reduce emissions, complementary to, or included in existing campaigns in Flanders, e.g. the 'burn wise' campaign (www.stookslim.be). Actions could include:

- Develop an online tool and associated guidance where potential consumers are guided to the cleanest wood stoves/boilers, including tips on how to use them.
- Introduce a voluntary label for vendors/retailers to advertise that their stoves are clean (analogy with energy efficiency labelling)
- Avoid wood burning on days with bad air quality and/or unfavourable meteorological conditions (e.g. fog)

9. Conclusion

The aim of this literature overview was to map real life emissions from residential wood combustion devices. It appears that the amount of tests conducted under real life conditions is rather limited. Differences between emissions under lab and real life conditions exist and are determined by multiple parameters. Most important in this regard are user behaviour and more specifically fuel characteristics.

Emission data from lab and pseudo real life tests indicate that significant variation exists in emissions from different types of wood combustion devices. A general trend that is observed, is that more recent devices emit less particulate matter compared to older devices, indicating that source control as emission reduction strategy is effective. Another approach for reducing emissions are end-of-pipe solutions. Different options exist, each with varying removal efficiencies and issues. Installing end-of-pipe solutions in retrofit on existing wood combustion devices, could be a possibility to reduce emissions, but operation conditions have to be carefully controlled.

Next to the primary emissions, wood combustion devices are also responsible for the formation of secondary organic aerosols. The precursors of these pollutants and the extent of their emissions due to residential wood combustion and their exact impact on air quality should be further investigated. Another issue that needs to be clarified is the unit for expression of emissions from wood combustion devices. Currently, two different types of units that are difficult to compare are used in scientific literature and legislation.

Four main policy recommendations are suggested from this literature overview. At first, a better understanding of emissions from wood combustion devices operated in real life should be obtained. Secondly, standard protocols for test procedures mimicking real life operation should be developed so that objective and realistic comparison between different wood combustion devices can be done. Furthermore, a national or regional strategy should be determined for the reduction of pollutant emissions from residential wood combustion and its impact on local air quality. At last, citizens should be informed about best practices concerning wood combustion.

10. References

Agoria-CIV. 2017. "Feiten En Cijfers over Houtverbranding : Hernieuwbare Energie Voor Huishoudelijke Verwarming."

Alves, Célia, Cátia Gonçalves, Ana Patrícia Fernandes, Luís Tarelho, and Casimiro Pio. 2011. "Fireplace and Woodstove Fine Particle Emissions from Combustion of Western Mediterranean Wood Types." *Atmospheric Research* 101 (3). Elsevier:692–700. https://doi.org/10.1016/J.ATMOSRES.2011.04.015.

Avagyan, Rozanna, Robin Nyström, Robert Lindgren, Christoffer Boman, and Roger Westerholm. 2016. "Particulate Hydroxy-PAH Emissions from a Residential Wood Log Stove Using Different Fuels and Burning Conditions." *Atmospheric Environment* 140 (September). Pergamon:1–9. https://doi.org/10.1016/J.ATMOSENV.2016.05.041.

Boman, Christoffer, Esbjörn Pettersson, Roger Westerholm, Dan Boström, and Anders Nordin. 2011. "Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 1: Pellet Stoves." *Energy & Fuels* 25 (1). American Chemical Society:307–14. https://doi.org/10.1021/ef100774x.

Brunner, T., I. Obernberger, and R. Scharler. 2009. "Primary Measures for Low-Emission Residential Wood Combustion - Comparison of Old with Optimised Modern Systems." *Proceedings of the 17th European Biomass Conference & Exhibition*.

Brunner, Thomas, Gerald Wuercher, and Ingwald Obernberger. 2017. "2-Year Field Operation Monitoring of Electrostatic Precipitators for Residential Wood Heating Systems." *Biomass and Bioenergy*, February. Pergamon. https://doi.org/10.1016/J.BIOMBIOE.2017.01.025.

Bruns, Emily A, Imad El Haddad, Jay G Slowik, Dogushan Kilic, Felix Klein, Urs Baltensperger, and André S H Prévôt. 2016. "Identification of Significant Precursor Gases of Secondary Organic Aerosols from Residential Wood Combustion." *Scientific Reports* 6 (June). Nature Publishing Group:27881. https://doi.org/10.1038/srep27881.

Calvo, A. I., V. Martins, T. Nunes, M. Duarte, R. Hillamo, K. Teinilä, V. Pont, et al. 2015. "Residential Wood Combustion in Two Domestic Devices: Relationship of Different Parameters throughout the Combustion Cycle." *Atmospheric Environment* 116:72–82. https://doi.org/10.1016/j.atmosenv.2015.06.012.

Calvo, A.I., L.A.C. Tarelho, C.A. Alves, M. Duarte, and T. Nunes. 2014. "Characterization of Operating Conditions of Two Residential Wood Combustion Appliances." *Fuel Processing Technology* 126 (October). Elsevier:222–32. https://doi.org/10.1016/J.FUPROC.2014.05.001.

Carnö, Johanna, Magnus Berg, and Sven Järås. 1996. "Catalytic Abatement of Emissions from Small-Scale Combustion of Wood: A Comparison of the Catalytic Effect in Model and Real Flue Gases." *Fuel* 75 (8). Elsevier:959–65. https://doi.org/10.1016/0016-2361(96)00047-6.

Carvalho, Ricardo Luis Teles de. 2016. "Wood-Burning Stoves Worldwide: Technology, Innovation and Policy," June. Aalborg Universitetsforlag. https://doi.org/10.5278/VBN.PHD.ENGSCI.00122.

Denier Van Der Gon, H A C, R Bergström, C Fountoukis, C Johansson, S N Pandis, D Simpson, and A J H Visschedijk. 2015. "Particulate Emissions from Residential Wood Combustion in Europe – Revised Estimates and an Evaluation." *Atmos. Chem. Phys* 15:6503–19. https://doi.org/10.5194/acp-15-6503-2015.

EEA. 2016. "EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016. Railways," no. 21:1–20. https://doi.org/10.2800/247535.

Eriksson, A. C., E. Z. Nordin, R. Nyström, E. Pettersson, E. Swietlicki, C. Bergvall, R. Westerholm, C. Boman, and J. H. Pagels. 2014. "Particulate PAH Emissions from Residential Biomass Combustion: Time-Resolved Analysis with Aerosol Mass Spectrometry." *Environmental Science & Technology* 48 (12). American Chemical Society:7143–50. https://doi.org/10.1021/es500486j.

Evtyugina, Margarita, Célia Alves, Ana Calvo, Teresa Nunes, Luís Tarelho, Márcio Duarte, Sónia O. Prozil, Dmitry V. Evtuguin, and Casimiro Pio. 2014. "VOC Emissions from Residential Combustion of Southern and Mid-European Woods." *Atmospheric*

Environment 83 (February). Pergamon:90–98. https://doi.org/10.1016/J.ATMOSENV.2013.10.050.

Fachinger, Friederike, Frank Drewnick, Reto Gieré, and Stephan Borrmann. 2017. "How the User Can Influence Particulate Emissions from Residential Wood and Pellet Stoves: Emission Factors for Different Fuels and Burning Conditions." *Atmospheric Environment* 158 (June). Pergamon:216–26. https://doi.org/10.1016/J.ATMOSENV.2017.03.027.

Fernandes, A. P., C. A. Alves, C. Gonçalves, L. Tarelho, C. Pio, C. Schimdl, and H. Bauer. 2011. "Emission Factors from Residential Combustion Appliances Burning Portuguese Biomass Fuels." *Journal of Environmental Monitoring* 13 (11):3196. https://doi.org/10.1039/c1em10500k.

Fine, Philip M., Glen R. Cass, and Bernd R. T. Simoneit. 2001. "Chemical Characterization of Fine Particle Emissions from Fireplace Combustion of Woods Grown in the Northeastern United States." American Chemical Society. https://doi.org/10.1021/ES001466K.

Fine, Philip M., Glen R. Cass, and Bernd R. T.. Simoneit. 2004. "Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Wood Types Grown in the Midwestern and Western United States." *Environmental Engineering Science* 21 (3):387–409. https://doi.org/10.1089/109287504323067021.

Fine, Philip M., Glen R. Cass, and Bernd R. T . Simoneit. 2002. "Chemical Characterization of Fine Particle Emissions from the Fireplace Combustion of Woods Grown in the Southern United States." American Chemical Society. https://doi.org/10.1021/ES0108988.

FOD, Health, Food Chain safety and Enviroment. n.d. "Website Containing All Approved Stoves on the Belfium Merket." Accessed December 13, 2017. https://apps.health.belgium.be/ordsm/02/f?p=500:6005:::NO:::

Gonçalves, Cátia, Célia Alves, Margarita Evtyugina, Fátima Mirante, Casimiro Pio, Alexandre Caseiro, Christoph Schmidl, Heidi Bauer, and Fernando Carvalho. 2010. "Characterisation of PM10 Emissions from Woodstove Combustion of Common Woods Grown in Portugal." *Atmospheric Environment* 44 (35). Pergamon:4474–80. https://doi.org/10.1016/J.ATMOSENV.2010.07.026.

Grieshop, A. P., J. M. Logue, N. M. Donahue, and A. L. Robinson. 2009. "Laboratory Investigation of Photochemical Oxidation of Organic Aerosol from Wood Fires 1: Measurement and Simulation of Organic Aerosol Evolution." *Atmospheric Chemistry and Physics* 9 (4):1263–77. https://doi.org/10.5194/acp-9-1263-2009.

Hartmann, Hans. 2012. "Technologie-Und Förderzentrum Im Kompetenzzentrum Für Nachwachsende Rohstoffe Status on Emissions, Regulation and Technical Improvements and Future Developments for Residential Wood Burning Appliances in Germany."

Hartmann, Hans, Claudia Schön, Peter Turowski, Friedrich Biedermann, Thomas Brunner, Linda Bäfver, John Finnan, and John Carroll. 2012. "Low Emission Operation Manual for Chimney Stove Users."

Hays, Michael D., N. Dean Smith, John Kinsey, Yuanji Dong, and Peter Kariher. 2003. "Polycyclic Aromatic Hydrocarbon Size Distributions in Aerosols from Appliances of Residential Wood Combustion as Determined by Direct Thermal Desorption - GC/MS." *Journal of Aerosol Science* 34 (8):1061–84. https://doi.org/10.1016/S0021-8502(03)00080-6.

Hukkanen, A., T. Kaivosoja, O. Sippula, K. Nuutinen, J. Jokiniemi, and J. Tissari. 2012. "Reduction of Gaseous and Particulate Emissions from Small-Scale Wood Combustion with a Catalytic Combustor." *Atmospheric Environment* 50 (April). Pergamon:16–23. https://doi.org/10.1016/J.ATMOSENV.2012.01.016.

Illerup, J.B., J. Nickelsen, B.B. Hansen, W. Lin, and K. Dam-Johansen. 2014. "Intelligent Heat System - High-Energy Efficient Wood Stoves with Low Emissions. Field Tests." *European Biomass Conference and Exhibition Proceedings*. ETA-Florence Renewable Energies, 689–94. https://doi.org/10.5071/22ndeubce2014-2bv.2.33.

Johnston, Olivia, Fay Johnston, John Todd, and Grant Williamson. 2016. "Community-Wide Distribution of a Catalytic Device to Reduce Winter Ambient Fine Particulate Matter from Residential Wood Combustion: A Field Study." Edited by Wenjun Ding. *PLOS ONE* 11 (11). Public Library of Science:e0166677. https://doi.org/10.1371/journal.pone.0166677.

Kaivosoja, T., A. Virén, J. Tissari, J. Ruuskanen, J. Tarhanen, O. Sippula, and J. Jokiniemi. 2012. "Effects of a Catalytic Converter on PCDD/F, Chlorophenol and PAH Emissions in Residential Wood Combustion." *Chemosphere* 88 (3). Pergamon:278–85. https://doi.org/10.1016/J.CHEMOSPHERE.2012.02.027.

Keller, Alejandro, and Heinz Burtscher. 2017. "Characterizing Particulate Emissions from Wood Burning Appliances Including Secondary Organic Aerosol Formation Potential." *Journal of Aerosol Science* 114 (December). Pergamon:21–30. https://doi.org/10.1016/J.JAEROSCI.2017.08.014.

Kelz, J., T. Brunner, I. Obenberger, P. Jalava, and M.-R. Hirvonen. 2010. "PM Emissions from Old and Modern Biomass Combustion Systems and Their Health Effects." In *18th European Biomass Conference*, 1231–43.

Kistler, Magdalena. 2012. "Particulate Matter and Odor Emission Factors from Small Scale Biomass Combustion Units."

Kocbach Bølling, Anette, Joakim Pagels, Karl Yttri, Lars Barregard, Gerd Sallsten, Per E Schwarze, and Christoffer Boman. 2009. "Health Effects of Residential Wood Smoke Particles: The Importance of Combustion Conditions and Physicochemical Particle Properties." *Particle and Fibre Toxicology* 6 (1). BioMed Central:29. https://doi.org/10.1186/1743-8977-6-29.

Lamberg, Heikki, Olli Sippula, Jarkko Tissari, and Jorma Jokiniemi. 2011. "Effects of Air Staging and Load on Fine-Particle and Gaseous Emissions from a Small-Scale Pellet Boiler." *Energy & Fuels* 25 (11). American Chemical Society:4952–60. https://doi.org/10.1021/ef2010578.

Lamberg, Heikki, Jarkko Tissari, Jorma Jokiniemi, and Olli Sippula. 2013. "Fine Particle and Gaseous Emissions from a Small-Scale Boiler Fueled by Pellets of Various Raw Materials." *Energy & Fuels* 27 (11). American Chemical Society:7044–53. https://doi.org/10.1021/ef401267t.

Mcdonald, Jacob D., Barbara Zielinska, Eric M. Fujita, John C. Sagebiel, Judith C. Chow, and John G. Watson. 2000. "Fine Particle and Gaseous Emission Rates from Residential Wood Combustion." *Environmental Science and Technology* 34 (11):2080–91. https://doi.org/10.1021/es9909632.

Nussbaumer, Thomas. 2017. "Aerosols from Biomass Combustion."

Nuutinen, K., J. Jokiniemi, O. Sippula, H. Lamberg, J. Sutinen, P. Horttanainen, and J. Tissari. 2014. "Effect of Air Staging on Fine Particle, Dust and Gaseous Emissions from Masonry Heaters." *Biomass and Bioenergy* 67 (August). Pergamon:167–78. https://doi.org/10.1016/J.BIOMBIOE.2014.04.033.

Obernberger, Ingwald, and Christoph Mandl. 2011. "Survey on the Present State of Particle Precipitation Devices for Residential Biomass Combustion with a Nominal Capacity up to 50 kW in IEA Bioenergy Task32 Member Countries Final Version." *IEA Task 32: Bioenergy Workshop*, no. December:1–105.

Orasche, Jürgen, Jürgen Schnelle-Kreis, Claudia Schön, Hans Hartmann, Hans Ruppert, Jose M. Arteaga-Salas, and Ralf Zimmermann. 2013. "Comparison of Emissions from Wood Combustion. Part 2: Impact of Combustion Conditions on Emission Factors and Characteristics of Particle-Bound Organic Species and Polycyclic Aromatic Hydrocarbon (PAH)-Related Toxicological Potential." *Energy and Fuels* 27 (3):1482–91. https://doi.org/10.1021/ef301506h.

Orasche, Jürgen, Torben Seidel, Hans Hartmann, Jürgen Schnelle-Kreis, Judith C. Chow, Hans Ruppert, and Ralf Zimmermann. 2012. "Comparison of Emissions from Wood Combustion. Part 1: Emission Factors and Characteristics from Different Small-Scale Residential Heating Appliances Considering Particulate Matter and Polycyclic Aromatic Hydrocarbon (PAH)-Related Toxicological Potential of Particle-Bound Organic Species." *Energy & Fuels* 26 (11). American Chemical Society:6695–6704. https://doi.org/10.1021/ef301295k.

Ozgen, Senem, Stefano Caserini, Silvia Galante, Michele Giugliano, Elisabetta Angelino, Alessandro Marongiu, Francesca Hugony, Gabriele Migliavacca, and Carmen Morreale.

2014. "Emission Factors from Small Scale Appliances Burning Wood and Pellets." *Atmospheric Environment* 94 (September). Pergamon:144–53. https://doi.org/10.1016/J.ATMOSENV.2014.05.032.

Ozil, Fabien, V. Tschamber, Frédéric Haas, and G. Trouvé. 2009. "Efficiency of Catalytic Processes for the Reduction of CO and VOC Emissions from Wood Combustion in Domestic Fireplaces." *Fuel Processing Technology* 90 (9). Elsevier:1053–61. https://doi.org/10.1016/J.FUPROC.2009.03.019.

Pettersson, Esbjörn, Christoffer Boman, Roger Westerholm, Dan Boström, and Anders Nordin. 2011. "Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 2: Wood Stove." *Energy & Fuels* 25 (1). American Chemical Society:315–23. https://doi.org/10.1021/ef1007787.

Poppel, Martine Van, Wim Aerts, Bart Bayens, Rob Brabers, Jan Peters, Maarten Spruyt, and Jo Van Laer. 2017. "Inschatting van de Bijdrage van Houtverbranding Door Burgers Aan Luchtverontreiniging in Vlaanderen."

Reichert, G., H. Hartmann, W. Haslinger, H. Oehler, R. Mack, C. Schmidl, C. Schön, et al. 2017. "Effect of Draught Conditions and Ignition Technique on Combustion Performance of Firewood Roomheaters." *Renewable Energy* 105 (May). Pergamon:547–60. https://doi.org/10.1016/J.RENENE.2016.12.017.

Reichert, G., C. Schmidl, W. Haslinger, M. Schwabl, W. Moser, S. Aigenbauer, M. Wöhler, and C. Hochenauer. 2016. "Investigation of User Behavior and Assessment of Typical Operation Mode for Different Types of Firewood Room Heating Appliances in Austria." *Renewable Energy* 93 (August). Pergamon:245–54. https://doi.org/10.1016/J.RENENE.2016.01.092.

Reichert, G., C. Schmidl, W. Haslinger, H. Stressler, R. Sturmlechner, M. Schwabl, N. Kienzl, and C. Hochenauer. 2017. "Long Term Durability and Safety Aspects of Oxidizing Honeycomb Catalysts Integrated in Firewood Stoves." *Biomass and Bioenergy* 105 (October). Pergamon:428–42. https://doi.org/10.1016/J.BIOMBIOE.2017.07.018.

Reichert, G., C. Schmidl, W. Haslinger, H. Stressler, R. Sturmlechner, M. Schwabl, M. Wöhler, and C. Hochenauer. 2018. "Catalytic Efficiency of Oxidizing Honeycomb Catalysts Integrated in Firewood Stoves Evaluated by a Novel Measuring Methodology under Real-Life Operating Conditions." *Renewable Energy* 117 (March). Pergamon:300–313. https://doi.org/10.1016/J.RENENE.2017.10.065.

Schleicher, Ole, Karsten Fuglsang, Peter Wåhlin, Helge Rørdam Olesen, Jacob Klenø Nøjgaard, and Max Bjerrum. 2011. "Test of Technologies for Flue Gas Cleaning and Combustion Improvement for Existing Residential Wood Burning Appliances."

Schmidl, Christoph, Markus Luisser, Emmanuel Padouvas, Leopold Lasselsberger, Magdalena Rzaca, Carlos Ramirez-Santa Cruz, Markus Handler, Ge Peng, Heidi Bauer, and Hans Puxbaum. 2011. "Particulate and Gaseous Emissions from Manually and Automatically Fired Small Scale Combustion Systems." *Atmospheric Environment* 45 (39). Pergamon:7443–54. https://doi.org/10.1016/J.ATMOSENV.2011.05.006.

Sevault, Alexis, Morten Seljeskog, Line Rydsa, Asbjorn Ostnor, Birger Ronning, Magnus Rishaug, and Norwegian Standard Ns. 2015. "Effect of Maintenance on Particulate Emissions from Residential Woodstoves."

Shen, Guofeng, Miao Xue, Siye Wei, Yuanchen Chen, Qiuyue Zhao, Bing Li, Haisuo Wu, and Shu Tao. 2013. "Influence of Fuel Moisture, Charge Size, Feeding Rate and Air Ventilation Conditions on the Emissions of PM, OC, EC, Parent PAHs, and Their Derivatives from Residential Wood Combustion." *Journal of Environmental Sciences (China)* 25 (9):1808–16. https://doi.org/10.1016/S1001-0742(12)60258-7.

Skreiberg, Øyvind. 2002. "Fuelsim -Average v1.1: A Mass, Volume and Energy Balance Spreadsheet for Continuous Combustion Applications."

Tissari, J., J. Lyyränen, K. Hytönen, O. Sippula, U. Tapper, A. Frey, K. Saarnio, et al. 2008. "Fine Particle and Gaseous Emissions from Normal and Smouldering Wood Combustion in a Conventional Masonry Heater." *Atmospheric Environment* 42 (34). Pergamon:7862–73. https://doi.org/10.1016/J.ATMOSENV.2008.07.019.

US EPA. 2015. "Environmental Protection Agency 40 CFR Part 60 Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air

Furnaces; Final Rule." *Federal Register* 80 (50).

Venturini, Elisa, Ivano Vassura, Francesca Agostini, Andrea Pizzi, Giuseppe Toscano, and Fabrizio Passarini. 2018. "Effect of Fuel Quality Classes on the Emissions of a Residential Wood Pellet Stove." *Fuel* 211 (January). Elsevier:269–77. https://doi.org/10.1016/J.FUEL.2017.09.017.

Vicente, E.D., and C.A. Alves. 2018. "An Overview of Particulate Emissions from Residential Biomass Combustion." *Atmospheric Research* 199 (January). Elsevier:159–85. https://doi.org/10.1016/J.ATMOSRES.2017.08.027.

Vicente, E.D., M.A. Duarte, A.I. Calvo, T.F. Nunes, L. Tarelho, and C.A. Alves. 2015. "Emission of Carbon Monoxide, Total Hydrocarbons and Particulate Matter during Wood Combustion in a Stove Operating under Distinct Conditions." *Fuel Processing Technology* 131 (March). Elsevier:182–92. https://doi.org/10.1016/J.FUPROC.2014.11.021.

VITO. 2017. "Home | EMIS." 2017. https://emis.vito.be/nl.

Vlaamse Milieumaatschappij. 2016. "Lozingen in de Lucht 2000-2016," 329.

VMM. 2016. "Luchtkwaliteit in Het Vlaamse Gewest. Jaarverslag Immissiemeetnetten - 2015."

Ward, Tony J, Christopher P Palmer, and Curtis W Noonan. 2010. "Fine Particulate Matter Source Apportionment Following a Large Woodstove Changeout Program in Libby, Montana." *Journal of the Air & Waste Management AssociationOnline) Journal Journal of the Air & Waste Management Association* 606:1096–2247. https://doi.org/10.3155/1047-3289.60.6.688doi.org/10.3155/1047-3289.60.6.688.

Wesenbeeck, K. Van, B. Hauchecorne, and S. Lenaerts. 2017. "Study of Positive and Negative Plasma Catalytic Oxidation of Ethylene." *Environmental Technology* 38 (12). Taylor & Francis:1554–61. https://doi.org/10.1080/09593330.2016.1237553.

WHO. 2015. "Residential Heating with Wood and Coal: Health Impact and Policy Options in Europe and North America Impact."

Win, Kaung Myat, and Tomas Persson. 2014. "Emissions from Residential Wood Pellet Boilers and Stove Characterized into Start-Up, Steady Operation, and Stop Emissions." *Energy & Fuels* 28 (4). American Chemical Society:2496–2505. https://doi.org/10.1021/ef4016894.

Win, Kaung Myat, Tomas Persson, and Chris Bales. 2012. "Particles and Gaseous Emissions from Realistic Operation of Residential Wood Pellet Heating Systems." *Atmospheric Environment* 59 (November). Pergamon:320–27. https://doi.org/10.1016/J.ATMOSENV.2012.05.016.

Wöhler, Marius, Jes Sig Andersen, Gero Becker, Henrik Persson, Gabriel Reichert, Claudia Schön, Christoph Schmidl, Dirk Jaeger, and Stefan K. Pelz. 2016. "Investigation of Real Life Operation of Biomass Room Heating Appliances – Results of a European Survey." *Applied Energy* 169 (May). Elsevier:240–49. https://doi.org/10.1016/J.APENERGY.2016.01.119.

Wöhler, Marius, Dirk Jaeger, Stefan K. Pelz, and Harald Thorwarth. 2017. "Potential of Integrated Emissions Reduction Systems in a Firewood Stove under Real Life Operation Conditions." *Energy & Fuels* 31 (7). American Chemical Society:7562–71. https://doi.org/10.1021/acs.energyfuels.7b00803.

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