Nordic Council
of Ministers

EMISSION FACTORS FOR SLCP EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION IN THE NORDIC COUNTRIES

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Preface

This project, Improved Nordic emission inventories of Short-Lived Climate Pollutants - SLCP, was proposed by the Swedish presidency of the Nordic Council of Ministers in 2013 and was approved in June 2013. It is planned for a four year period and all five Nordic countries participate and contribute actively in the work. The project is financed by the Nordic Council of Ministers.

The overall objective of the project is to improve the Nordic emission inventories of Short Lived Climate Pollutants (SLCP). This is in line with the Svalbard Declaration on Short-lived Climate Forcers[1] from 2012, where the the Nordic environment ministers, among other things, declared that they will actively strive to:

- act as a driving force and work more closely together in international fora to advocate more ambitious international regulation of emissions of greenhouse gases and SLCFs
- develop national measures to reduce emissions from transport and from the inefficient use of woodburning as a source of heating, which will also have positive regional effects on health and the climate
- further develop and strengthen national emissions accounts for SLCFs, alongside separate accounts for black carbon.

The first phase of the project presented an analysis of the status of knowledge (TN2015:523). This report presents the results from the second phase of the project, the implementation of an emission measurement program, where the objective is to expand the knowledge and develop well documented emission factors for SLCP and $PM_{2.5}$ from residential wood combustion.

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[1] http://www.norden.org/en/nordic-council-of-ministers/council-of-ministers/the-nordic-council-of-ministers-for-the-environment-mr-m/declarations-and-statements/svalbard-declaration-on-short-lived-climate-forcers-27.03.-2012

The work has been excellently guided by a project steering group with participants from the Nordic countries as well as from the Nordic Council of Ministers.

Göteborg, 14 November 2017

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Summary

The overall objective of this project is to improve the Nordic air emission inventories of Short Lived Climate Pollutants (SLCP). As a first step a Background analysis was performed (Kindbom et al., 2015). That report assesses and summarises current Nordic knowledge, emission inventories and emission levels, and lays the basis for the emission measurement program which was performed in this second phase of the project.

In order to improve the national emission inventories of SLCP, and reduce uncertainties, a better understanding of the emission factors for residential wood combustion is essential. Apart from emission factors, also national activity data on wood combustion technologies, fuel consumption and combustion conditions are important.

This project contributes to a better knowledge base for emission factors for $PM_{2.5}$, EC, OC, CH_4, NMVOC and CO from residential wood combustion, as well as ratios for increased emissions at "bad combustion conditions" which can be weighted into the national emission factors, depending on national circumstances.

Emission measurements were conducted on residential wood burning appliances, boilers and stoves, representative for the Nordic countries. There are substantial differences in the stock of residential wood burning technologies between the five Nordic countries, but the common technologies in all countries were covered.

Measurements were made using EN standards for boilers and for stoves, and also the Norwegian standard for stoves. Sampling for $PM_{2.5}$, EC and OC were in all cases done in a dilution tunnel (i.e. sample including condensables) and not in hot flue gases.

The technologies tested were grouped according to similarities in technology and emission levels when developing the emission factors. In a national emission inventory, lack of very detailed activity data on technologies is the common situation, why the emission factor results were adapted accordingly.

Generally the older technologies exhibited higher emission levels than more modern types of equipment. For example, the traditional log wood boilers had emission levels that were in the order of 5–10 times higher (depending on pollutant) than for the modern log wood boilers or pellet boilers. Among the stoves the difference was not as large, with up to 2 times higher emission levels from the traditional tiled and masonry stoves, and an older type iron stove, compared to the modern wood stoves.

Several test conditions in addition to those prescribed by the EN standards were investigated. This was done in order to capture some of the variation in emission levels arising from various user practices impacting the quality of combustion and resulting emission levels. The standard conditions, nominal heat load and standard fuel moisture, were thus extended to include tests using moist fuel or part heat load conditions on most of the tested appliances. A few tests were also made with drier fuel, higher heat loads, or entering smaller batches of wood than prescribed in the standards.

Part load combustion conditions in the boilers increased the emissions between 2–6 times, while moist fuel generally increased the emission levels by a factor of 1.5–2. The modern stoves were sensitive to moist fuel, where emissions of for example $PM_{2.5}$ and OC increased in the order of 5–8 times compared to when fired with standard fuel. The older technologies, tiled and masonry stoves, were on the other hand hardly affected by moist fuel, and the emission levels were comparable to the standard fuel test cases. The higher impact from moist fuel in the modern stoves is likely due to limited capacity of the air systems in many modern stoves. For the stoves, part load conditions generally increased the emission levels by 1.5–3.5 times.

To improve the national emission inventories of SLCPs the large sensitivity to operational conditions (moist fuel and part load) needs to be taken into consideration in national emission inventories, where "real life" emissions are estimated. Country-specific assessments on shares of "bad combustion conditions" are essential to properly weigh bad combustion into the national emission factors.

It was found that the EC emission factors did not correlate with the $PM_{2.5}$ emission factors, and that the EC emissions were less affected by moist fuel and part load conditions than most of the other pollutants. In many cases in the literature, EC emission factors are given as percentage of $PM_{2.5}$, which according to the results in this project does not necessarily reflect reality very well.

When comparing currently used national emission factors in the Nordic countries with those developed from the measurement program in this project, it is obvious that there are sometimes large differences, both between countries and in relation to the measurement results. There are examples of individual national emission factors that are both considerably higher, or considerably lower, than the measurement results.

The comparison highlights discrepancies in the emission factors between the Nordic countries. One of the reasons for differences between current national factors is that they are based on measurement results derived using different measurement standards (e.g. hot flue gases/diluted sampling, or EN standards/Norwegian standard). In order for national emission inventory results to be comparable, a harmonisation of emission factor levels is needed, unless there are real differences between the countries. The results from this project provides a foundation for developing emission inventories that are more comparable between the Nordic countries.

The measurement results and the emission factors developed in this work increases the knowledge base for estimating emissions of SLCPs (and $PM_{2.5}$) with less uncertainties in the future. However, the measurement program also showed that there can be quite a large variabilty when repeating identical test cases, why additional well designed measurements would add information that can be used for refining the emission factors to reflect reality with higher certainty.

1. Background

The overall objective of the current project is to improve the Nordic emission inventories of Short Lived Climate Pollutants (SLCP). As a first step a Background analysis was performed (Kindbom et al., 2015). That report assesses and summarises current Nordic knowledge, emission inventories and emission levels, and lays the basis for the emission measurement program which was performed in this second phase of the project.

As described in the Background analysis (Kindbom et al., 2015), residential biomass combustion is identified as a major emission source for SLCPs in the Nordic countries.[2] It was concluded that emission inventories currently reported are not comparable between the countries. This applies especially to particulate matter ($PM_{2.5}$, BC) where different measurement standards are used for the emission measurements to derive national emission factors. Furthermore, it was concluded that there are differences between the Nordic countries in the stock of technologies and in the user practices for residential biomass combustion. Currently used emission factors for BC include rather high uncertainties since they are based on comparatively few measurements, which imply that the reported emission inventories include large uncertainties.

SLCP is the acronyme for Short Lived Climate Pollutants, which is a group of substances comprising black carbon (BC) or soot, tropospheric ozone (O_3), methane (CH_4), and hydrofluorocarbons. O_3 is formed in atmospheric chemical reactions involving CH_4, nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and sunlight. The SLCPs have, in comparison to the long lived greenhouse gases e.g. carbon dioxide (CO_2) and nitrous oxide (N_2O), a short residence time in the atmosphere.

Elemental Carbon (EC) is often used interchangeably with Black Carbon (BC) in development of emission factors. EC and BC are defined by their method of analysis, where EC is analysed thermally, while BC is analysed optically. Theoretically EC comprises only carbon, while BC can also include other dark and optically detectable compounds. In practice, when used in national emission inventories with their general level of uncertainties, these differences can most likely be disregarded. In the measurement program presented in this report EC was analysed and reported. Another component of particulate matter, Organic Carbon (OC) was also analysed. OC is considered to have a cooling impact on the climate.

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[2] In Iceland, emissions from residential biomass combustion have not been estimated as of today. In contrast to other Nordic countries, the great majority of residences uses either (geothermal) district- or electric heating, suggesting a much lower impact of residential combustion of biomass on total national SLCP emissions than in the other Nordic countries. In addition, the small population of Iceland compared to other Nordic countries suggests, overall, a very small impact of the Icelandic residential combustion of biomass on total Nordic SLCP emissions.

Both Elemental Carbon (EC) and Organic Carbon (OC) are thus components in the particulate matter fraction, which is smaller than 2.5 µm in diameter ($PM_{2.5}$). The accuracy of $PM_{2.5}$ emission inventories is regarded as key for estimating emissions of BC/EC and OC. Therefore $PM_{2.5}$ emissions were also analysed in this project.

For residential wood combustion in general, information on emission factors for BC is internationally scarce, with some exceptions (e.g. recent results from measurements on Norwegian stoves, under Norwegian conditions, and some measurements in Finland). In the Finnish and Norwegian emission inventories national emission factors for BC are used where available, while the Danish and Swedish BC emission inventories, at present, rely on information on BC as a fraction of emitted $PM_{2.5}$ from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EMEP/EEA, 2016). In this report, a comparison is made between the information presented in the Guidebook and the results from measurements carried out as part of this project.

Presently there is no defined measurement standard prescribed as a basis for $PM_{2.5}$ emission factor development within the CLRTAP convention (or EU). It is stated in the EMEP/EEA Guidebook (EMEP/EEA, 2016) that recent international studies based on diluted flue gas sampling were prioritised when updating the Guidebook. In addition, emission data that includes the whole combustion cycle were prioritised as the emission during ignition, part load and burnout are much higher than at full load conditions.

Emission factors for PM based on different emission measurement standards (hot flue gases or diluted) may give significantly different results. A comparative study of the sampling methods showed that the emission factors found when using a dilution tunnel are between 2.5 and 10 times higher than when only taking into account the solid particles measured directly in the chimney (Nussbaumer et al., 2008). A similar range is also reported by Bäfver (2008). For comparability and compliance purposes, the important issue is to base the estimates on comparable measurement standards, irrespective of the standard. For modelling purposes and in assessment of health effects, it seems that results from diluted sampling would be favored, since those data are considered to better reflect real conditions in the atmosphere after an emission has occurred.

As residential biomass combustion is such a dominating source of $PM_{2.5}$ and BC emissions in the Nordic countries, the present uncertainties and knowledge gaps need to be reduced in order to be able to use the inventory results as a sufficiently reliable basis for policy development and actions. The results from the measurement program in this project aims to provide information to improve the reliability of reported emission levels of SLCP and $PM_{2.5}$ from residential wood combustion in the Nordic conditions.

2. Measurements

Particulate matter ($PM_{2.5}$), Elemental Carbon (EC), Organic Carbon (OC), Black Carbon (BC), methane (CH_4), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO) emissions were measured from residential biomass combustion appliances that are widely used in the Nordic countries. The measurement program and the methods to use were developed based on the conclusions from the Background analysis from the previous stage of the project (Kindbom et al., 2015).

Both boilers and room heaters (stoves) were tested. The test objects, operating conditions, test methods, sampling and analysis, as well as results of the measurement program are presented in detail in Carlsson et al., 2016. In this report information from Carlsson et al., 2016, is presented at a general level to enable understanding of the reasoning and interpretation of the results in relation to the emission factors proposed in Chapter 5. The measurements were performed in cooperation between SP Technical Research Institute of Sweden (boilers) and DTI, Danish Technological Institute (stoves).

2.1 Test methods, sampling and analysis

Most of the firing cycles were performed according to EN standards (EN 303–5 for boilers and EN 16510-series for room heaters). Sampling during the ignition phase is not included in EN standards, but was added in this measurement program. A few tests using firing schemes according to Norwegian standards, NS 3058, were performed for stoves to enable comparison of differences in particle emission levels ($PM_{2.5}$, EC and OC) due to the measurement standard followed.

In the EN standard series valid during 2015 for residential appliances, no test on part load for log-wood fired conventional room heaters is provided. Therefore, tests for part loads available in the revision of EN 16510 (endorsed in March 2016) were used.

All sampling for particulates ($PM_{2.5}$, EC, OC, BC) was done in a full flow dilution tunnel according to specifications in NS3058. Samples were collected on quartz filters for subsequent analysis. Analysis of $PM_{2.5}$ was made gravimetrically, while EC/OC were analysed thermo-optically according to NIOSH protocol 870. BC was analysed optically (using an OT21 aethalometer) on the filter samples before they were analysed for EC and OC.

The results for BC from the aethalometer analyses show a weak correlation with the EC results, and BC results were considerably lower than the EC results, generally about one third (Carlsson et al., 2016). This was regarded as questionable results, since in theory BC should be on the same level or higher than the EC results. Due to that the NIOSH protocol 870 for analysis of EC is a more established method than the aethalometer analysis (including the calculation algorithm) for BC, the BC results were not further taken into consideration in the analysis of the measurement results.

Sampling for gaseous compounds, total organic gaseous carbon (TOC) and CH_4, was done in undiluted flue gases in the chimney. Measurements were made with continuous FID-analysers with a "methane cutter". NMVOC was calculated as the difference between TOC and CH_4. CO in the flue gases was determined by CO infrared analysers.

2.1.1 Conversion from C to NMVOC and CH_4

Total organic gaseous carbon (TOC) was measured as well as methane (CH_4). NMVOC is calculated as the difference between TOC and CH_4, all based on their carbon content. Results for CH_4 and NMVOC are given from the measurements as mg Carbon/MJ. CH_4 is easily converted from the weight of carbon to the weight of the molecule CH_4 to get emission factors in the unit mg CH_4/MJ. NMVOC, however, is a mixture of carbon containing organic compounds. A conversion factor from the amount of carbon to the amount of NMVOC was calculated based on profiles of organic gaseous compounds measured in emissions from residential wood and pellet stoves in Sweden (Pettersson et al., 2011).[3]

The weighted fraction of carbon in the mixture was found to be 0.88. To convert the results from amount carbon (mg C/MJ) to mg NMVOC/MJ the results were multiplied by 1/0.88, or 1.13.

2.2 Test cycles and sampling periods

Both for boilers and for stoves, the standard test methods include a start-up and pre-test period to establish stable thermal conditions, but during which the emissions are not measured according to the test procedures. As the start-up phase is expected to result in higher emissions, PM sampling was carried out on separate filters during this period to facilitate determination of EC/OC and $PM_{2.5}$ emissions to distinguish them from emissions during stable periods.

For wood log boilers, a test cycle of one ignition and pre-test period was followed by two consecutive test periods with one fuel batch each. The ignition and pre-test period included loading of two batches of wood. The first (smaller batch) is for lighting up the fire, and the second is added after three minutes when the first sampling for 30 minutes starts.

During the ignition and pre-test periods one sample was taken, and during the two following fuel batches, three samples were taken during each batch. In summary, seven samples were taken during one test cycle (in most cases). Sampling of emissions was

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[3] The data actually used in the calculations is compiled in the data base Speciate, v. 4.5. (https://www.epa.gov/air-emissions-modeling/speciate-version-45-through-32, accessed, 11 November 2016).

made during periods of 30 min, the first one (ignition and pre-test period) beginning 3 minutes after fuel loading.

For stoves, in principle the same procedures were applied, apart from that extra sampling during the ignition phase was only included in a few test cycles. Each test cycle, apart from tests at reduced heat output, consisted of three test periods with one fuel batch and one sample during each fuel batch. Test cycles at reduced heat output (part load) consisted of two test periods with one fuel batch and one sample in each test period. The test according to NS3058 consisted of three or four test periods as prescribed by the Norwegian standard. The number of test periods depended on the capacity of combustion air inlets, as the highest prescribed rate was not possible to achieve for one stove.

2.3 Test program

The boilers and stoves tested in the program are described with some short technical characteristics in Table 1 The boilers and stoves tested were chosen to each represent a typical technology. The objective of the test program was to obtain results that can be useful in national emission inventory work. In inventory work very detailed information on the residential combustion equipment is generally not available. The technical characteristics of the types of boilers and stove in Table 1 allows for grouping and weighing test results according to available national information on residential combustion technologies.

Table 1: Types of boilers and room heaters (stoves) in the test program

Notation	Type of boiler/stove
Boilers	
P1	Log wood boiler with inverse combustion and λ-probe. Ceramic grate.
P2	Log wood boiler I with inverse combustion and flue gas fan. Ceramic grate.
P3	Log wood boiler II with inverse combustion and flue gas fan. Ceramic grate. Different manufacturer than P2
P4	Log wood boiler with inverse combustion and natural draught. Ceramic grate.
P5	"Simple" log wood boiler made from cast iron, natural draught and upward combustion
P6	Old combination boiler (oil + wood), upward combustion
P7	Traditional pellet burner in an combination boiler
P8	Advanced pellet burner with λ-probe in boiler designed for pellet firing
P9	Pellet boiler with integrated grate burner with λ-probe, pilot flame
P10	Wood chip boiler with λ-probe, pilot flame
Stoves	
A0	Modern medium class wood stove
A1	Traditional simple stove (DIY stove)
A2	Modern popular wood stove
A3	State-of-the-art room heater
A4	Traditional Nordic cast iron stove
A5	Traditional Nordic tiled stove
A6	Traditional Nordic slow heat release appliance (masonry stove)
A7	Swedish type pellets stove (now obsolete)
A8	European type pellets stove
A9	Traditional Nordic sauna stove

The measurement program includes tests at nominal load, but also at part load (reduced heat output) and at high load to simulate user practices that are expected to lead to higher emissions. Part load tests were carried out at 30% of nominal heat load, a level relevant both from a heat load point of view as well as being somewhat of the lowest possible heat load. The part load tests are assumed to lead to inefficient combustion conditions. This happens when the air supply is intentionally reduced in order to allow combustion to proceed unattended during a considerable amount of time. This leads to inefficient combustion conditions, which is expected to increase SLCP emission levels.

High load tests were performed on a few stoves. The nominal heat load is not necessarily the maximum heat load for stoves used in a living area. The maximum heat load would, however, be obtained e.g. if the fuel batch is large, the combustion air inlets are fully open and the fuel is dry. Entering more firewood than the stove is optimized for leads to shortage of combustion air, which in turn leads to higher emissions during quite short time periods. Therefore such high load tests were made for two stoves.

Furthermore, a few tests were made investigating variations of ignition practice for stoves (top-down ignition vs bottom-up ignition). For boilers the influence on emission levels of entering small batches of wood at part load firing instead of one larger batch was also tested.

To further simulate high-emission user practices, tests with moist and moderately dry log wood were performed in addition to using log wood with standard moisture content. The use of moist log wood is expected to increase emissions due to inefficient combustion during evaporation of the moisture in the fuel. Too dry fuel may also lead to increased emissions. Moderately over-dried firewood (8–12%) may not have significant adverse influence on the emissions, but it is generally recognized that extremely dry firewood (0–5%), e.g. waste wood from industrial manufacture of windows or floors, is too dry to burn properly and is likely to cause excessive emissions of soot. Extremely dry firewood was not tested in this test program, only moderately over-dried.

Fuel characteristics for the standard, moist and dry test fuels are presented in Table 2.

Table 2: Fuel moisture content for the standard fuel, moist fuel and dry fuel tests

Fuel type	Moisture content (%)
Standard log wood (SLW)	16–20
Moist log wood (MLW)	25–30
Dry log wood (DLW)	10–14
Wood pellets (WP)	≤ 12
Standard wood chips (SWC)	20–30
Moist wood chips (MWC)	40–50

An overview of the test program for boilers is presented in Table 3 and for stoves in Table 4.

2.3.1 Boilers

For modern boilers designed to be connected to an accumulator tank, only tests at nominal load were included (P1–P4) (Table 3). A log-wood boiler which is connected to an accumulator tank is normally only operated at its nominal output, loading the accumulator. Part load operation is not expected.

For log-wood boilers which are not generally connected to an accumulator tank (P5 and P6), operation at part loads is expected to occur frequently. This happens as the operator fires according to the momentary heat need of the house. Therefore, such boilers were tested at both its nominal heat output as well as at a part load of 30%.

Pellets and wood chips boilers (P7–P10) are normally designed to operate within a heat output range of at least 30–100%. Therefore, pellet and wood chip boilers were tested at both their nominal heat output as well as at a part load of 30%.

Both standard, moist and dry fuels were tested in the boilers, as outlined in Table 3.

Table 3: Test cases for boilers

Appliance	Test designation	Heat load	Test fuel
P1	P1NomSLW	Nominal	Standard log wood
	P1NomMLW	Nominal	Moist log wood
P2	P2NomSLW	Nominal	Standard log wood
	P2NomMLW	Nominal	Moist log wood
	P2NomDLW	Nominal	Dry log wood
P3	P3NomSLW	Nominal	Standard log wood
P4	P4NomSLW	Nominal	Standard log wood
	P4NomMLW	Nominal	Moist log wood
	P4NomDLW	Nominal	Dry log wood
P5	P5NomSLW	Nominal	Standard log wood
	P5NomMLW	Nominal	Moist log wood
	P5PartSLW	Part	Standard log wood
P6	P6NomSLW	Nominal	Standard log wood
	P6PartSLW	Part	Standard log wood
P7	P7NomWP	Nominal	Wood pellets
	P7PartWP	Part	Wood pellets
P8	P8NomWP	Nominal	Wood pellets
	P8PartWP	Part	Wood pellets
P9	P9NomWP	Nominal	Wood pellets
	P9PartWP	Part	Wood pellets
P10	P10NomSWC	Nominal	Wood chips
	P10NomMWC	Nominal	Moist wood chips
	P10PartSWC	Part	Wood chips
	P10PartMWC	Nominal	Moist wood chips

2.3.2 Stoves

The stoves tested are shown in Figure 1 and an overview of the test cases is presented in Table 4.

Figure 1: The stoves (room heaters) tested

A1 Simple stove
A2 Modern stove
A3 State -of-the-art
A4 Traditional cast iron
A5Tiled stove
A6 Masonry stove
A8 Pellet stove
A9 Sauna stove

All stoves were tested at their nominal heat output, and tests at part load were performed for most of the stoves (A0–A5, A8) (Table 4). Residential appliances are normally heating the air in the living area through heat radiation and operation of the stove at part loads is a common situation.

Slow heat release appliances are designed to be fully heated up during combustion of one or two fuel batches at high intensity, after which the accumulated heat is discharged to the surrounding air during a long time period, up to two days. This means that only testing at high intensity (nominal load) combustion is relevant for the masonry stove (A6). This reasoning is also valid for sauna stoves (A9).

The nominal heat load is not necessarily the maximum heat load for stoves used in a living area. Therefore a few tests with high load were performed for two stoves (A1 and A2).

The relation between particle emissions ($PM_{2.5}$, EC and OC) when tested according to the EN-related scheme and according to the Norwegian Standard (NS3058) was achieved conducting measurements according to NS3058 for two residential appliances (A1–A2). Emissions measured according to NS3058 provides emission figures that are directly related to the test method. The NS requires four tests at four different burn rates, which means that the stoves are tested also under less favorable combustion conditions with reduced burning rates. Emissions according to NS3058 are higher than emissions figures from EN16510, and the differences is primarily due to the testing on low load. This leads to much higher emissions than what the stove is optimized for. The results from the four loads are weighted together to form a "mean value" with some emphasis on low load operation.

As for boilers, tests with the different fuel qualitites (standard, moist and dry) were also made (Table 4). Tests according to the Norwegian standard were made using fuel as specified in NS3058.

Table 4: Test cases for stoves

Appliance	Test designation	Heat load	Test fuel
A0	A0NomSLW	Nominal	Standard log wood
	A0PartSLW	Part	Standard log wood
A1	A1NomSLW	Nominal	Standard log wood
	A1NomMLW	Nominal	Moist log wood
	A1PartSLW	Part	Standard log wood
	A1HighSLW	High	Standard log wood
	A1NomDLW	Nominal	Dry log wood
	A1HighDLW	High	Dry log wood
	A1NS3058*	NS3058*	NS3058*
A2	A2NomSLW	Nominal	Standard log wood
	A2NomMLW	Nominal	Moist log wood
	A2PartSLW	Part	Standard log wood
	A2HighSLW	High	Standard log wood
	A2NomDLW	Nominal	Dry log wood
	A2NS3058*	NS3058*	NS3058*
A3	A3NomSLW	Nominal	Standard log wood
	A3NomMLW	Nominal	Moist log wood
	A3PartSLW	Part	Standard log wood
A4	A4NomSLW	Nominal	Standard log wood
	A4PartSLW	Part	Standard log wood
A5	A5NomSLW	Nominal	Standard log wood
	A5PartSLW	Part	Standard log wood
A6	A6NomSLW	Nominal	Standard log wood
	A6NomMLW	Nominal	Moist log wood
A8	A8NomWP	Nominal	Wood pellets
	A8PartWP	Part	Wood pellets
A9	A9NomSLW	Nominal	Standard log wood
	A9NomMLW	Nominal	Moist log wood

Note: * NS3058= Norwegian standard.

3. Measurement results

3.1 Measurement results for boilers

An overview of the measurement results from the boiler tests are shown in Table 5 and Figure 2. The test case P2NomSLW (modern boiler, nominal heat load and standard log wood) was repated three times. This was done as part of exploratory tests performed to examine and decide on test conditions before the ordinary test programme was started. All the other tests were performed once, in most cases including seven samples during the combustion test cycle.

Table 5: Emission results for boilers as mean values over all sampling periods in each test (from Carlsson et al., 2016)

Test designation*	$PM_{2,5}$ mg/MJ	EC mg/MJ	OC mg/MJ	CO mg/MJ	CH_4 mg/MJ[6]	NMVOC mg/MJ[7]
P1NomSLW	24	2	12	233	4	32
P1NomMLW	46	2	8	178	2	13
P2NomSLW [1]	29	3	10	1054	10	64
P2NomMLW	50	4	13	1335	18	145
P2NomDLW	32	3	12	754	8	56
P3NomSLW	45	8	19	2036	32	141
P4NomSLW	36	15	14	1516	23	>135[5]
P4NomMLW	32	5	14	1894	35	212
P4NomDLW	89	9	36	3160	62	279
P5NomSLW	320	19	>96[2]	3578	103	477
P5NomMLW	524	>31[2]	>143[2]	4748	>28[2]	>272[2]
P5PartSLW	1138	15	>426[2]	8978	>35[2]	>551[2]
P5PartMLW [3]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
P6NomSLW	317	27	138	2963	47	>462[5]
P6PartSLW	1975	35	776	6408	259	>1332[5]
P6PartSLW small batches	373	21	181	3437	74	932
P7NomWP	57	14	11	631	4	22
P7PartWP	182	17	54	1225	6	57
P8NomWP	38	2	12	134	1	9
P8PartWP	>14[5]	7	16	250	1	10
P9NomWP	15	1	6	120	1	15
P9PartWP	88	6	49	2273	26	218
P10NomSWC	48	1	20	366	4	47
P10NomMWC [4]	61	6	25	1894	11	94
P10PartSWC	227	7	98	4479	64	627
P10PartMWC [4]	718	14	>367[5]	5839	81	950

Note: *Nom=Nominal load, Part=Part load, SLW=Standard log wood, MLW=Moist log wood, DLW=Dry log wood, WP=Wood pellets, SWC=Standard wood chips, MWC=Moist wood chips.

[1] Mean value from all samples of the three exploatory tests.

[2] Measurement only part of time. Actual value higher.

[3] Test not performed due to bad combustion already during P5PartSLW.

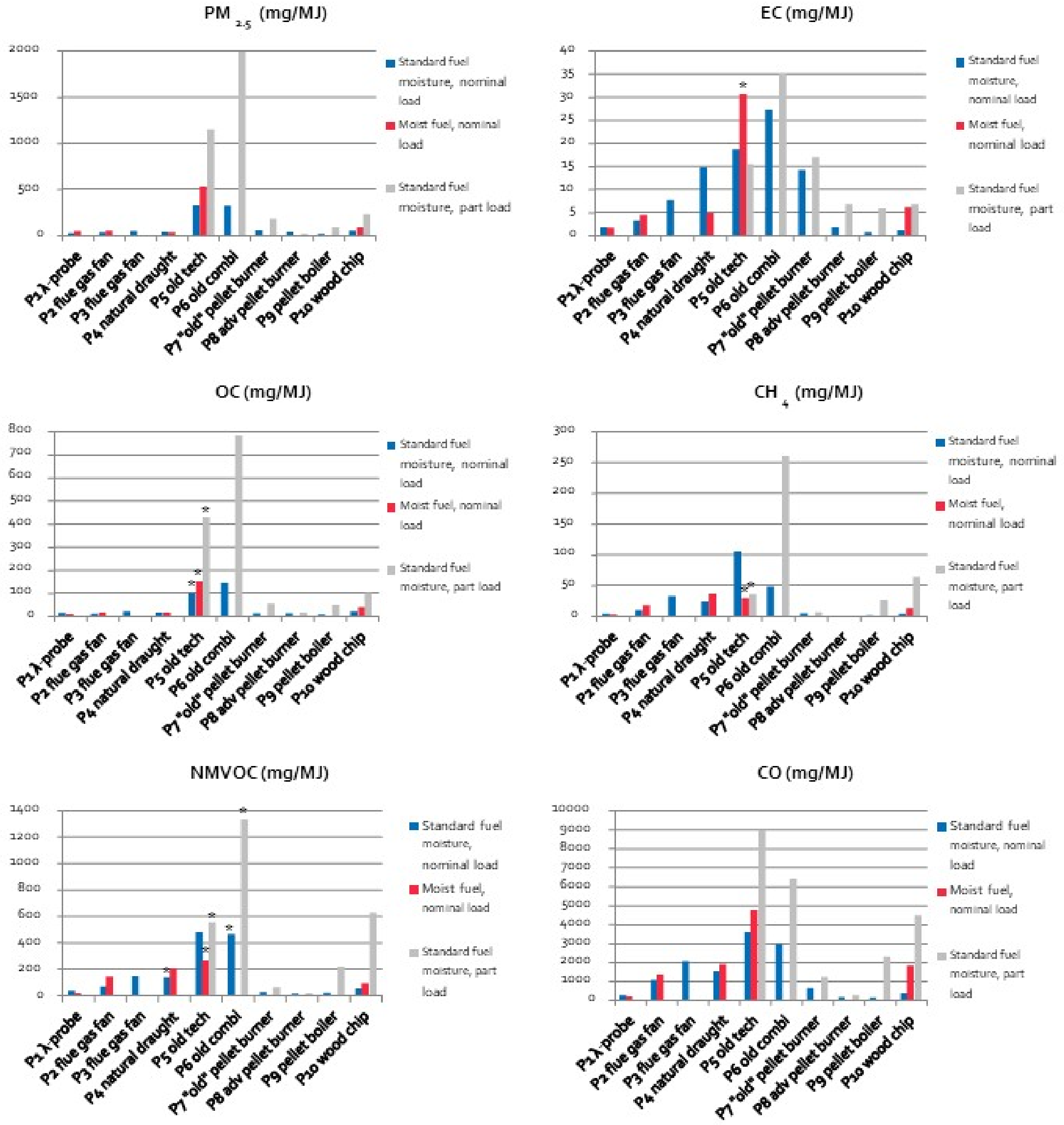
[4] Not possible to ignite on moist wood chips. Values from ignition taken from P10PartSWC.

[5] Some samples above measurement range. Actual value higher.
n.a.= not available

[6] Measured values (mgC/MJ) are converted to mg CH_4 using a conversion factor of 16/12=1.33.

[7] Measured values (mgC/MJ) are converted to mg NMVOC using a conversion factor of 1.13.

Figure 2: Average emissions from boilers, standard fuel (SLW, WP or SWC) and moist fuel (MLW or MWC) and nominal and part load



Note: *=actual value higher.

3.1.1 *Boiler types and general emission levels*

The overall result from the test program show clearly higher emission levels from the two old technology boilers (P5 and P6) than from the other tested boilers, when comparing results from tests at nominal heat load using standard fuel (blue bars in Figure 2). For EC the difference is not as pronounced as for the other substances.

The modern boilers P1–P4 are equipped with modern combustion technology. i.e. inverse combustion and ceramic insulated combustion chamber. In three cases a flue gas fan is installed (P1–P3) and in one case also a λ-probe (P1) for excess air control. When tested at nominal load and standard fuel these boilers show emission results that are very low when comparing all boiler types within the test program. The data for modern log wood boilers (nominal load and standard fuel) reflects to a quite large extent the common use of these boilers; i.e. operating connected to an accumulator tank and using wood that has been dried outside but under cover.

Boiler P5 represents a simple combustion technology, and boiler P6 is an old combination boiler intended for both wood and fuel oil firing. None of these two boilers have any of the features listed for the modern boilers above. These two older technology boilers showed the highest emissions.

All three pellet fired boilers (P7–P9) show emissions that are comparable to, or slightly lower than the four modern log wood boilers (P1–P4). P7 is an old combination boiler, not designed for pellet firing, but where a separate pellet burner is installed. This type of pellet boiler installation is the most common in Sweden. P8 and P9, on the other hand, are designed for pellet firing. P8 has a separate advanced pellet burner installed and P9 has an integrated grate designed for pellet combustion.

The wood chip boiler (P10) also showed emission levels (nominal load, standard fuel) comparable to the modern log wood boilers and the pellet boilers.

3.1.2 Impact of fuel quality, boilers

The measurements show that the impact of moist fuel (red bars in Figure 2) is towards higher emission levels, about 1.5 times, compared to when firing with standard fuel (blue bars in Figure 2). In several cases, however, the levels are similar. For the old technology boiler (P5) the actual emission levels for CH_4 and NMVOC using moist fuel are higher than shown in Figure 2. During the measurements the instruments were disconnected since the measurement range was exceeded.

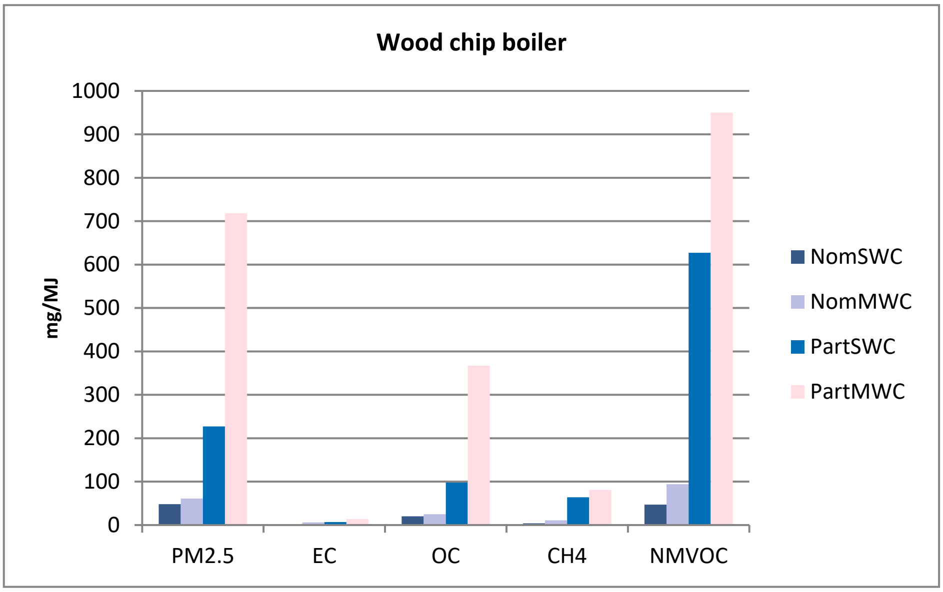
For the modern type boilers tested with moist fuel (P1, P2 and P4) the influence of using moist fuel instead of standard fuel is rather weak for $PM_{2.5}$, EC and OC, and emission levels are low. A somewhat higher influence can be seen for NMVOC and CH_4.

For the old technology boiler, P5, the emission level of $PM_{2.5}$ when using moist fuel is about 1.5 times that from standard fuel firing. Also EC and OC emission levels are clearly higher. Since the measurement instruments for CH_4 and NMVOC had to be disconnected from sampling, the level of the influence of moist fuel on those substances is not known from the results, other than that it is most likely significant.

The larger impact on emission levels from moist fuel in older technology boilers (P5) compared to in modern boilers (P1–P4) seem reasonable when looking at the combustion conditions in the different boiler types. In a modern log wood boiler only a small part of the fuel load is taking part in the combustion at any given time; the rest gradually approaching the combustion zone by gravity. During this process, the fuel is continuously dried and then volatilized. The conditions are held almost constant at feasible temperatures in the primary combustion zone; thereby generating reasonably low emissions even with moist fuel. On the other hand, in a traditional boiler as P5, the full fuel load is burning at the same time, meaning that in the beginning of the combustion cycle the total amount of fuel must be dried, then volatilized and finally the char is combusted. This in turn means that combustion temperatures and combustion conditions are varying widely over the combustion cycle. Significantly higher emissions at least during parts of the cycle is the natural result.

No tests were made with moist fuel for the pellet boilers while the wood chip boiler (P10) was tested with moist fuel, both at nominal and at part load. The combination of moist fuel and part load results in very much higher emissions for all substances, except for EC (Figure 3). This test case may not be that common in reality, as it was impossible to ignite using the moist wood chips. Ignition had to be made with standard wood chips, while the subsequent loadings of fuel during the test cycle were done with moist wood chips.

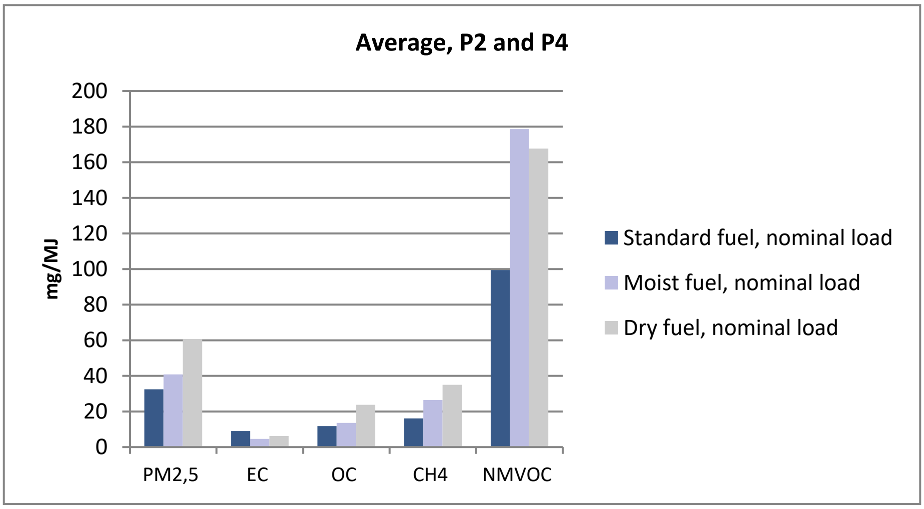
Figure 3: Emission levels at all test cases for the wood chip boiler (P10)



Note: Nom=nominal load, Part= part load, SWC=standard wood chips, MWC=moist wood chips.

A few test cases on modern log wood boilers (P2 and P4) using dry log wood indicate somewhat higher emissions than when using standard wood (except for EC), but the effect is rather weak. The dry wood tests produced emissions that were slightly higher than, or on comparable levels to the moist wood tests (Figure 4). The tests indicated a better performance, irrespective of fuel moisture, for the boiler with a flue gas fan (P2) while emissions from the boiler with natural draught (P4) were somewhat more affected. All measured emissions from the two modern boilers are however considerably lower than the old technology boiler (P5) and the old combi boiler (P6).

Figure 4: Average results from tests of different fuel qualities on the modern log wood boilers (P2 with flue gas fan and P4 with natural draught). Nominal heat load and standard fuel (SLW), moist fuel (MLW) and dry fuel (DLW)



3.1.3 Impact of heat load, boilers

The impact of heat load was tested comparing standard fuel at nominal heat load and at part heat load. The modern log wood boilers were not tested at part load since they are expected to be connected to an accumulator tank, and therefore fired at nominal heat load.

In almost all cases, emissions are much higher at part load (inefficient combustion conditions) than at nominal heat load (blue bars in Figure 2. The differences are generally between 2–6 times, and even higher for NMVOC, CH_4 and CO for the wood chip boiler.

The EC emissions for the old technologies (P5, P6 and P7) are an exception in that they do not differ much between part load and nominal load.

For the advanced pellet boilers and for the wood chips boiler, all emissions were significantly higher at part load than at nominal heat load, though at low absolute levels. Both pellet fired boilers and wood chip boilers are normally not connected to an accumulator tank and are therefore operated directly against the momentary heat demand of the house. This means that the "real-life emissions" for these boiler types might be closer to the part load values than to the nominal load numbers.

3.2 Measurement results for stoves

An overview of the measurement results from the stove tests are shown in Table 6 and in Figure 5. Two or three repeated identical tests were made in the exploratory phase for stove A0, A1 and A2 at nominal load using standard log wood (NomSLW). Repeated tests were also made for part heat load and standard log wood (PartSLW) using stove

A0 and A2. All the other tests were performed once, in most cases including three samples during the combustion cycle.

Table 6: Stoves/residential heaters. Summary of emission data as mean values over all sampling periods in each test (from Carlsson et al., 2016)

Test designation*	$PM_{2,5}$ mg/MJ	EC mg/MJ	OC mg/MJ	CO mg/MJ	CH_4 mg/MJ[3]	NMVOC mg/MJ[4]
A0NomSLW[1]	78	9	39	2287	153	144
A0PartSLW[1]	81	19	46	2730	193	120
A1NomSLW[2]	93	42	11	1107	52	19
A1NomMLW	821	18	441	3839	368	772
A1PartSLW	94	6	14	1777	67	7
A1NomDLW	150	19	8	931	59	14
A1HighDLW	287	104	44	2223	91	98
A1HighSLW	208	n.a.	n.a.	785	35	5
A1NS3058	347	31	167	n.a.	n.a	n.a.
A2NomSLW[2]	53	18	21	1077	35	40
A2NomSLW+TD**	62	14	23	1043	45	47
A2NomMLW	348	9	91	3078	160	267
A2PartSLW+BU**	137	27	43	1838	120	105
A2PartSLW+SB ***	458	12	191	3084	245	495
A2NomDLW	72	10	23	656	37	21
A2HighSLW	131	44	49	1628	72	127
A2NS3058	430	120	149	n.a	n.a	n.a.
A3NomSLW	106	3	6	919	31	28
A3NomMLW	100	4	25	1490	80	71
A3PartSLW	74	4	7	1386	11	1
A4NomSLW	147	13	48	1165	65	132
A4PartSLW	330	15	127	2194	187	322
A5NomSLW	198	122	70	3145	167	229
A5PartSLW	285	110	75	2751	272	154
A6NomSLW	82	22	31	1585	61	133
A6NomMLW	78	7	22	1175	65	76
A8NomWP	100	10	11	189	1	3
A8PartWP	153	7	24	447	4	14
A9NomSLW	104	18	52	1405	56	85
A9NomMLW	120	28	51	2030	107	180

Note:

[1] Average of 3 exploratory tests.

[2] Average of 2 exploratory tests.

[3] Measured values (mgC/MJ) are converted to mg CH_4 using a conversion factor of 16/12=1.33.

[4] Measured values (mgC/MJ) are converted to mg NMVOC using a conversion factor of 1.13.

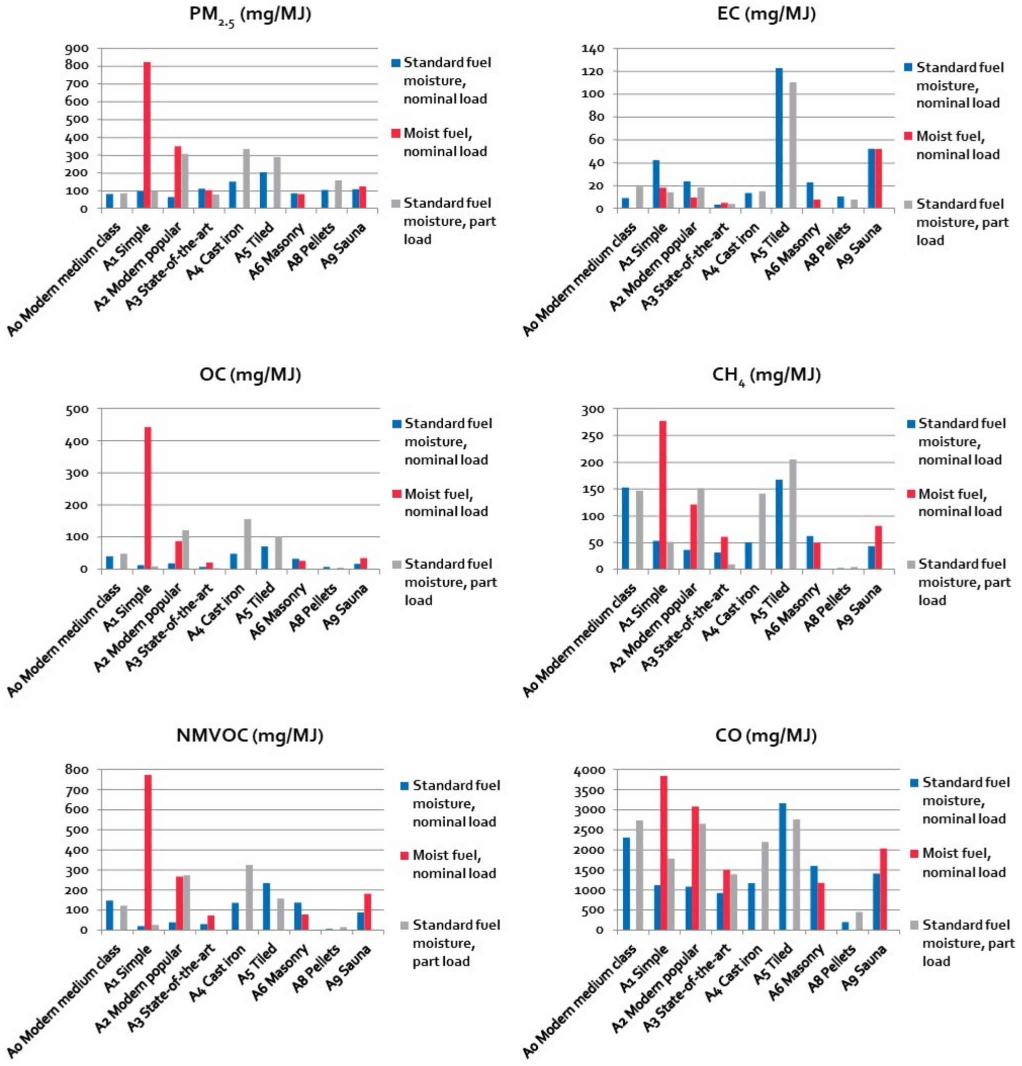
*Nom=Nominal load, Part=Part load, High=High load, SLW=Standard log wood, MLW=Moist log wood, DLW=Dry log wood, WP=Wood pellets, NS3058=Test according to Norwegian standard 3058 ($PM_{2.5}$, EC, OC).

** TD= Top-Down ignition, BU= Bottom-Up ignition. Ignition data are included in average values in table, but not in figures below.

*** SB= Small Batches.

n.a= not available.

Figure 5: Average emissions from stoves/residential heaters, standard fuel (SLW or WP) and moist fuel (MLW) and nominal and part load



3.2.1 *Types of stoves and general emission levels*

The measurements at nominal load and standard fuel (blue bars in Figure 5) show that the difference in emission levels between older and more modern technologies in general are not as pronounced for stoves as they are for boilers.

The highest emission levels at nominal load and standard fuel were measured from the old tiled stove (A5). Emissions were generally on the higher side also from the other older type technology stoves (i.e. the masonry stove (A6) and cast iron stove (A4)), but also for some of the modern stoves (e.g. A0 and A1).

The state-of-the-art stove (A3) and the pellet stove (A8) generally performed well, showing the lowest emission levels for most substances.

The tiled stove (A5) and the sauna stove (A9) work solely or predominantly on primary air supply. They both display significantly higher EC emissions than the remaining stoves. This is most likely due to their very basic air systems where most or all of the combustion air enters as primary air, leading to substantial soot formation. In terms of emission levels, all stoves, except for the tiled stove (A5) and the sauna stove (A9) and to some extent the simple modern stove (A1), display fairly low EC emissions.

The newer stoves A0-A3 display on average lower levels of particle emissions ($PM_{2.5}$ and OC) than the older stoves A4 and A5. This is due to enhanced start-up properties in general among the newer stoves.

3.2.2 Impact of fuel quality, stoves

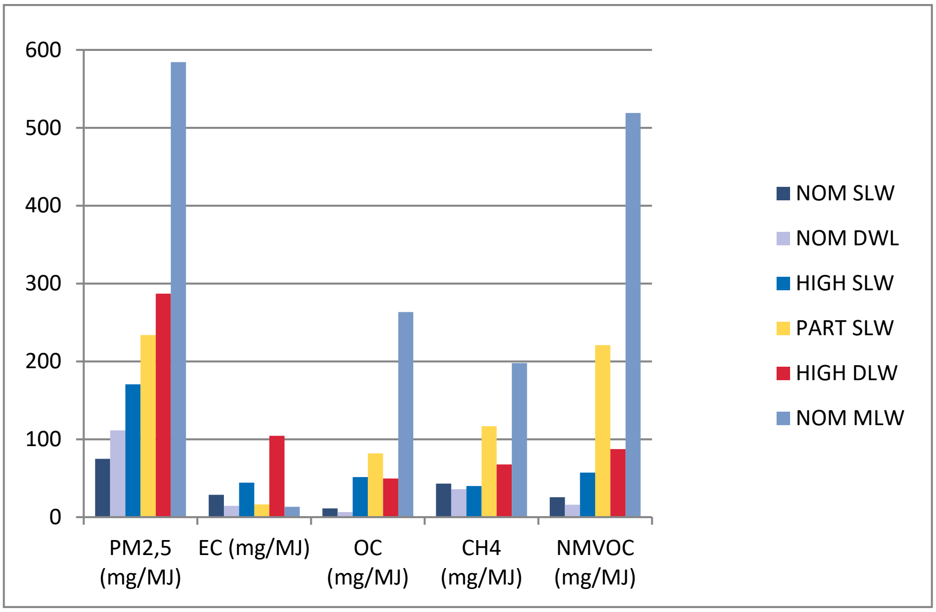
The impact of using moist fuel wood (red bars in Figure 5) instead of fuel with standard moisture (blue bars in Figure 5) seems to vary a lot between technologies.

For the modern stoves (A1 and A2) moist fuel resulted in much higher emissions than when using standard fuel quality (except for EC). The state-of-the-art stove (A3), the masonry stove (A5) and the sauna stove (A9) seem much more robust against moist firewood and emission levels are more similar to those measured from standard fuel firing. There are reasons to believe that the higher impact from moist fuel in the modern stoves is mainly due to limited capacity of the air systems among many modern stoves.

Two tests using moderately dry log wood was performed on stoves A1 and A2. In Figure 6 the average results from all the different test cases for A1 and A2 are shown, including those already presented in Figure 5.

The firing of moderately dry log wood at nominal heat load (NOM DLW) did not have as large impact on emission levels compared to the moist fuel wood (NOM MLW), and levels were closer to the standard log wood results. In fact, for all substances, except for $PM_{2.5}$, firing with moderately dry log wood gave somewhat lower emissions than when using standard log wood.

Figure 6: Average results from all test cases performed on stoves A1 and A2. Nom=Nominal load



Note: High=high load, Part=part load, SLW=Standard log wood, DLW=dry log wood, MLW=moist log wood.

According to the measurement results emissions of EC react differently to firewood moisture than $PM_{2.5}$ and OC emissions. Among the modern stoves A1 and A2, where all three firewood qualities were tested, EC emissions from both the moist and the dry firewood are lower than from the standard log wood at nominal load (Figure 5). This is also the case for the masonry stove (A6). For the state-of-the-art stove (A3) and the sauna stove (A9), EC emissions are of similar magnitude, independent of whether the firing is done with standard fuel or with moist fuel (Figure 5).

3.2.3 *Impact of heat load, stoves*

The impact of firing with part heat load (grey bars in Figure 5) instead of nominal heat load (blue bars) generally results in emission levels that are in the order of at least twice as high for a modern popular stove (A2) and a traditional cast iron stove (A4). For two of the modern stoves (A0 and A1) the firing with part load did not have any large effect on emission levels compared to the firing at nominal load. This may be due to variabilities in measurements (see chapter 3.7).

For the tiled stove (A5) part heat load firing resulted in higher emissions than at nominal load, but the difference is not as pronounced as for the stoves A2 and A4. The clearly lowest emission levels at part load firing were measured from the state-of-the-art stove (A3) and the pellets stove (A8) for most substances. Emissions from the state-of-the-art stove (A3) at part load were for most substances lower than at nominal load. This may be due to the fact that it is difficult to steer an automatically controlled stove like the A3 into reduced heat output because the valve is beyond manual control.

There is no clear dependency between heat load and the magnitude of the EC emissions. For about half of the stoves, the part load and nominal load EC emissions are of the same magnitude.

A few tests were also performed firing with high heat load on the modern stoves A1 and A2. The results show that overloading modern stoves with firewood (high load) leads to higher emission levels than when firing at nominal load (HIGH SLW compared to NOM SLW in Figure 6). On average the emission doubled for most substances (except for CH_4) when stoves A1 and A2 were fired at high load instead of at nominal load. The modern stoves are prone to react to firewood overload because of their optimized air systems. In order to reduce the heat output to the room, many modern stoves have downsized air capacity, when comparing to 10–15 year old stoves.

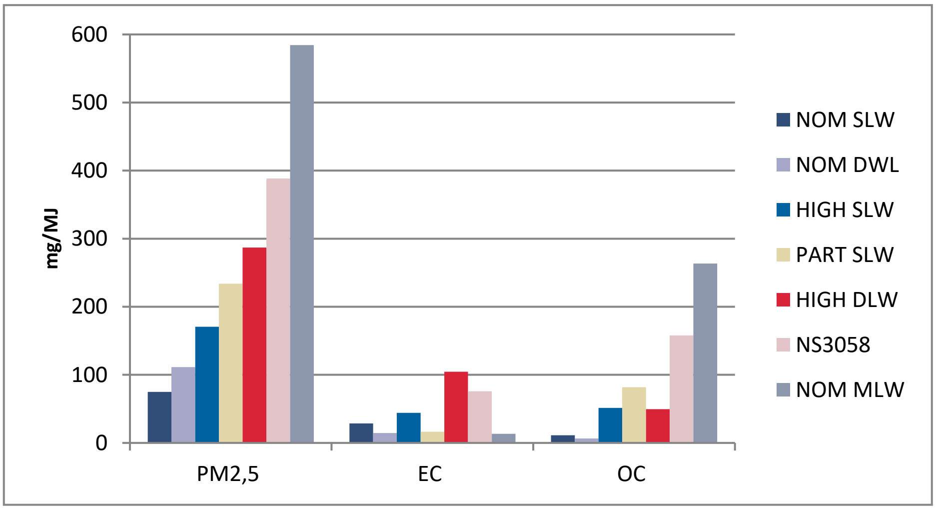
As was also the case for the boilers, EC emissions show no general apparent dependence on heat load or fuel moisture.

3.3 Impact of measurement standard, stoves

Presently, the emission factors used in the Nordic countries are based on tests using different standards. Only in Norway the Norwegian standard (NS3058) is the basis for emission factors for particulate matter. Since there are reasons to suspect differences in measured emission levels due to measurement standards, a few tests were performed to be able to compare $PM_{2.5}$, EC and OC emissions using the NS3058 firing scheme and the EN 16510 firing scheme. The tests were made on stoves A1 and A2, a traditional simple stove and a modern popular stove. In all cases sampling was done in a dilution tunnel. Calculations and weighing of results where done according to the standards.

Average resuts from all tests cases on stoves A1 and A2, including the NS3058-tests, are presented in Figure 7.

Figure 7: Results from testing according to Norwegian standard (NS3058) compared to all other test combinations using EN16510 for stoves A1 and A2



Combining the results for the stoves A1 and A2, NS3058 weighted average $PM_{2.5}$ emission is 5 times the ordinary nominal load (NOM) standard log wood (SLW) emission, but only 66% of the moist log wood (MLW) emission. Also for EC and OC the NS3058 results are much higher than nominal load and standard fuel tests, about 3 times for EC and >10 times for OC.

3.3.1 Comparison of NS3058 test results and Norwegian emission factors

The current emission factors for Norway are based on Norwegian standard measurements. In Table 7 the factors currently used in Norway for stoves produced after 1998 (comparable to "modern stoves") are presented, together with the NS3058 test results for the modern stoves A1 and A2 presented above. In Norway there are also national emission factors (higher) for stoves older than 1998 (see table 26 in chapter 5.3). Revised emission factors have recently been proposed by Seljeskog et al., (2016), but have so far not been adopted as national factors. These are also presented in the table below. The recently evaluated and proposed emission factors are lower than those presently used in the Norwegian national inventory.

The NS3058 test results for $PM_{2.5}$ from new stoves are about half of those used as national emission factors in the Norwegian national emission inventory. Measured factors for EC are on the other hand about 30% higher while OC factors are about one fourth of the Norwegian currently used emission factors (Table 7).

One contributing reason for the differences between the test results and the Norwegian emission factors may be the variability of measurements (see chapter 3.7 for discussion on uncertainty). The recently proposed emission factors by Seljeskog et al., (2016) are closer to the ones measured in this project.

Weighted Norwegian emission factors are calculated based on the amount of wood used in the different wood stove categories. The current weighting procedure involves separating open fireplace and stoves produced before and after 1998, and using reduced emission factors for large cities, where less part load operation is assumed.

The weighting according to the current method is for the emission inventory 2015 based on the following categories: stoves produced before 1998, 40.1%, stoves produced after 1998, 55.1% and fireplaces 4.9%. The assumed amount of wood used in large cities is 6.1% and the rest of the country, 93.9%.

Seljeskog et al. also proposes a revised weighting procedure. As before, a distinction of fireplaces and stoves produced before and after 1998 is suggested, but then stoves are again divided into two categories, part load and nominal load operated. Seljeskog et al. suggests this to be a more realistic distinction than the current assumption of different emission factors for large cities and the rest of the country.

The weighting according to the proposed revised method is as follows:

- old stoves (before 1998), 65% part load and 35% nominal load
- new stoves (after 1998), 70% part load and 30% nominal load.

Table 7: Results from two tests using the Norwegian standard (NS3058) on modern stoves in this project, compared to current Norwegian emission factors for stoves produced after 1998, and recent evaluations by Seljeskog et al. 2016 (mg/MJ)

	This project	Current Norwegian emission factors for stoves produced after 1998 (mg/MJ)		Recent evaluation by Seljeskog et al. 2016		
Modern stoves	Modern stoves, NS3058	Norway, includes night firing	Norway, larger cities, no night firing	Norway, part load firing	Norway, nominal load firing	Emission factors assuming 70% part load and 30% nominal load
PM2.5	388 (347–430)	758	690	619	113	467
EC	76 (31–120)	51	54	40	35	39
OC	159 (149–167)	623	551	346	84	267

3.4 Impact of ignition, boilers and stoves

The first sample in each test cycle for the boilers represents the ignition (and pre-test) phase. In the boiler tests two batches of wood were added in the beginning of the test. The first (smaller batch) is for lighting up the fire, and the second is added after three minutes when the first sampling for 30 minutes starts.

The ignition phase has commonly been thought to result in higher emissions than the following burn period. However, the results showed that emissions are not higher during ignition in all cases, and that for some boilers and pollutants the ignition phase results in lower or approximately the same level of emissions as during the following sampling periods of the test cycle.

In Figure 8 and Figure 9 results for the ignition and pre-test period are shown separately from the following sampling periods in the test cycles, for modern log wood boilers and for traditional boilers. For the modern log wood boilers the values during the ignition and pre-test periods are higher than during the following sampling periods. For the traditional wood log boilers, the emissions during the ignition and pre-test periods are instead lower than during the following sampling periodes (except for EC).

Figure 8: Modern log wood boilers (P1–P4). Average of ignition and pretest sampling periods (ign) compared to the average for the follwing sampling periods, and the average for all sampling periods (average)

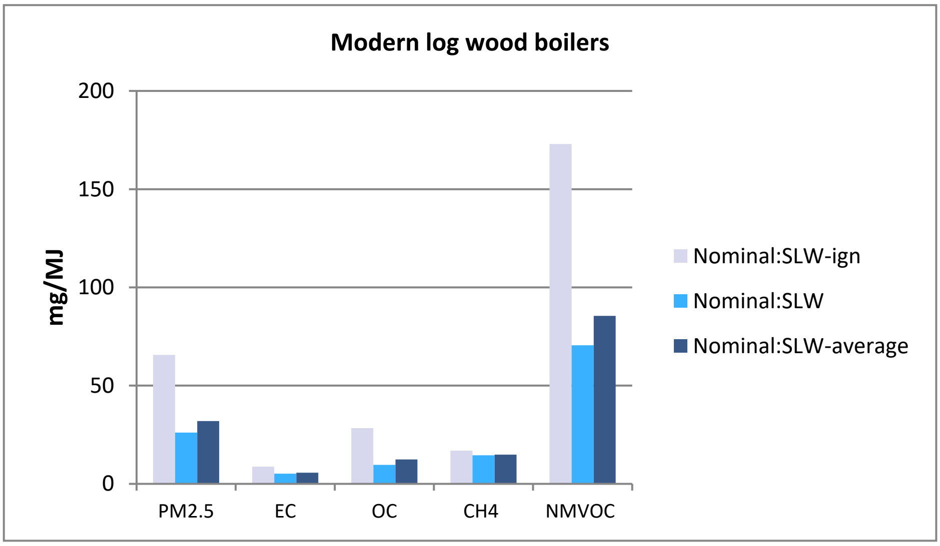
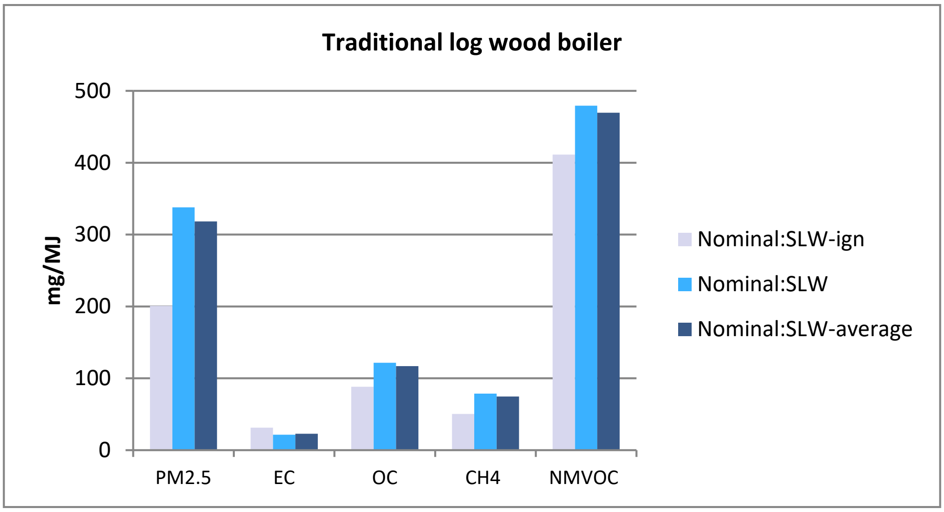


Figure 9: Traditional log wood boilers (P5–P6). Average of ignition and pretest sampling periods (ign) compared to the average for the follwing sampling periods, and the average for all sampling periods (average)

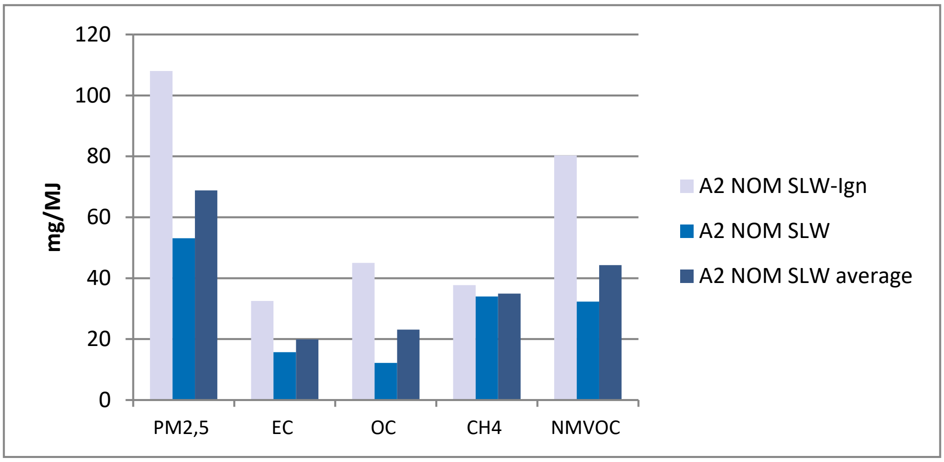


The somewhat unexpected results showing lower emissions during the ignition and pre-test periods for traditional boilers show that the ignition phase does not necessarily result in higher emissions than the actual combustion phase.

In absolute numbers, the tests show that the emissions at ignition in traditional wood log boilers (Figure 9) are around three times higher than the ignition phase in the modern boilers (Figure 8).

For the stoves, sampling during the ignition phase was only made during two special tests on stove A2. In both cases standard log wood was used. In Figure 10 the average of the emissions at ignition is compared with emissions during the following sampling periods. The tests indicate that emissions at ignition are approximately twice as high as during the subsequent repeated combustion periods for all substances except for methane where the difference is much smaller.

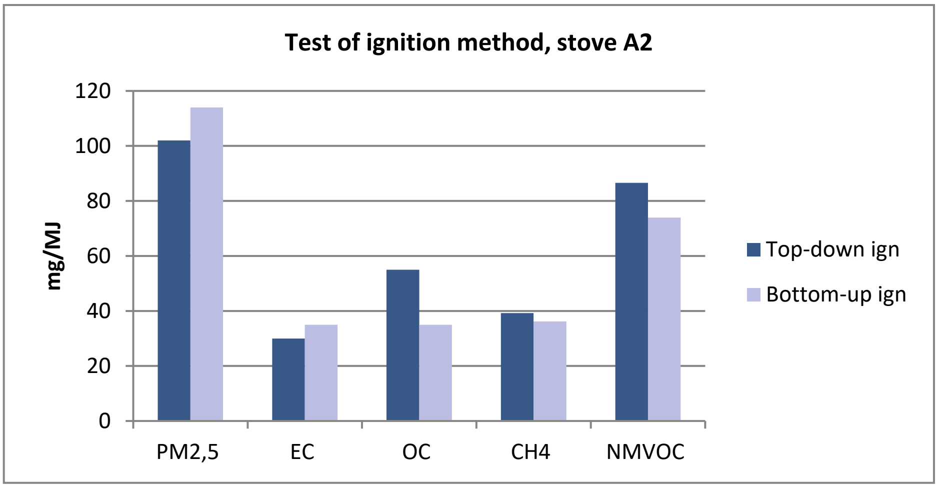
Figure 10: Stove A2. Average of ignition and pre-test sampling periods (ignition) compared to the average for the following sampling periods during the test cycles, and the average of all sampling periods



As expected, the emissions are higher during the ignition period for stove A2 than during the subsequent repeated burn cycles. Earlier it was a general assumption that the PM ratio was even higher. Technological development among wood stoves in recent years has led to stoves having better firebox insulation and better air systems, both effective in allowing a rapid start-up sequence, yielding a robust fire and higher firebox temperatures sooner for the benefit of lower emissions.

For the A2 stove, which is the average stove widespread in Sweden, tests were carried out using the traditional bottom-up ignition and the top-down ignition, which in recent years has been recommended by environmental agencies in Scandinavia since it is assumed to result in lower emissions. In Figure 11 the emissions sampled at the bottom-up ignition and the top-down ignition periods are compared.

Figure 11: Test of bottom-up ignition and top-down ignition on stove A2



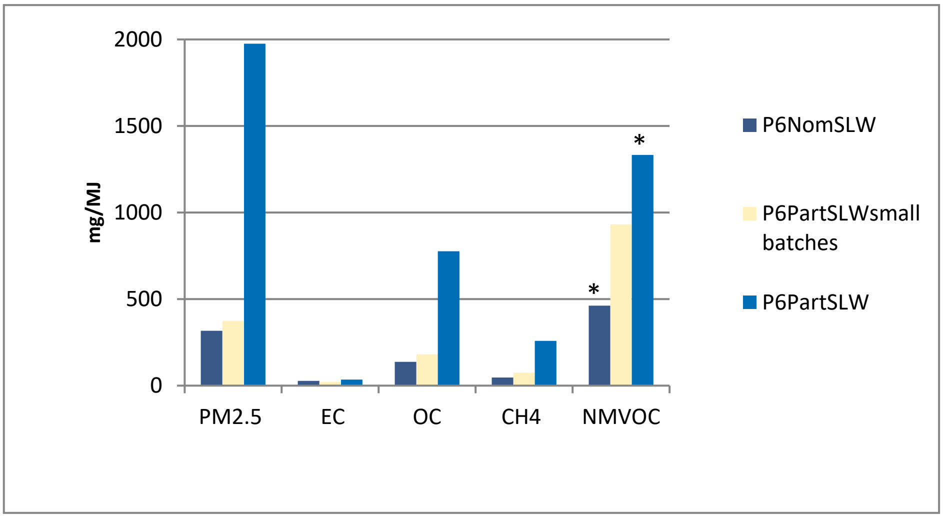
It's clearly seen that all emissions are of approximately the same order of magnitude when ignition is carried out by a skilled operator in a well-controlled test lab environment. However, it is the general assumption that, among average stove users, the top-down ignition method leads to lower emissions because the fire is never excessively roared up, meaning that the pyrolysis gases can be burnt in the order they are released from the firewood. For example, recent tests in Denmark have shown reducions of emissions between 0–75%, with an average reduction of particle emissions of 23% at ignition, if the top-down method is used instead of bottom-up ignition (Andersen & Hvidberg, 2017). The conclusion in the report is that top-down ignition is preferred, but that the effect varies between stoves.

3.5 Impact of operation: loading small fuel batches at part load firing, boilers and stoves

To investigate the impact of operation when firing at part load conditions, test cases adding the fuel more often and in smaller batches were performed. The tests were conducted using the old combination boiler, P6, and one of the modern stoves, A2.

The emissions measured at nominal heat load, at part heat load and at part heat load with small fuel batches are presented in Figure 12 for boiler P6. Standard log wood was used in all three cases.

Figure 12: Emissions at nominal and part heat load, and at part heat load with fuel feeding in small batches. Boiler P6, standard fuel (SLW)

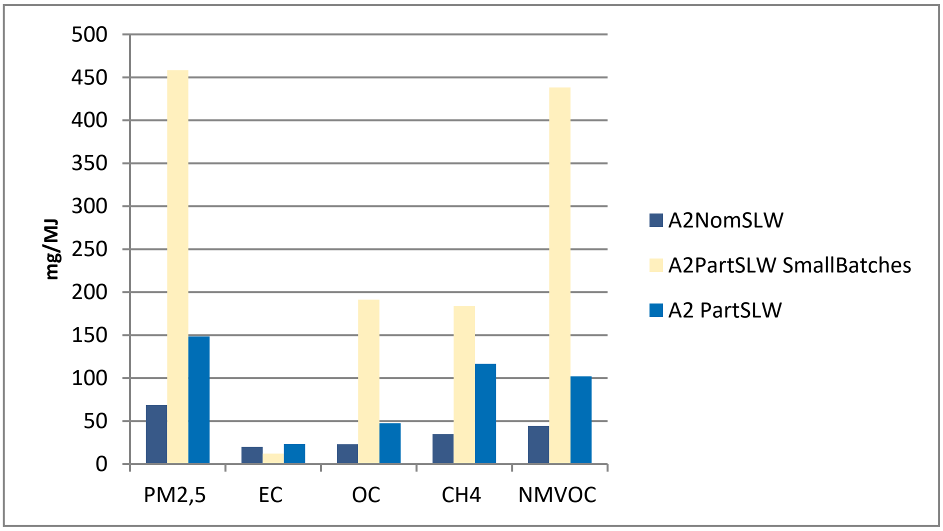


Note: * Actual values are higher.

The results show that operating the boiler with small fuel batches at part load (i.e. shorter time between fuel loadings) causes the emissions to decrease quite dramatically compared to the case at part heat load with fewer, but larger, fuel loadings. The "small batches" way of firing approaches more constant, and favourable, combustion conditions. This type of operation, however, requires the presence of the user during firing.

A corresponding test with small fuel batches was carried out in one test case using stove A2. In Figure 13 the results show that, for the A2 stove, the small batches part load case actually produced higher emissions than the part load with fewer but larger batches (except for EC). Both part load test cases resulted in higher emissions than the case with nominal heat load. This is not the expected outcome, but might be a result of a higher sensitivity to variations in combustion conditions in modern stoves with limited capacities of the air system.

Figure 13: Results for stove A2, impact of small batches at part load



3.6 EC and OC as fraction of $PM_{2.5}$

EC and also OC emission factors are sometimes expressed as a fraction of $PM_{2.5}$ emission factors, a convenient way of estimating emissions (EEA, 2016). However, the results shown in Figure 14 indicate that EC emissions do not correlate with $PM_{2.5}$ emissions over the burn cycle for the tests carried out in this study. For OC, on the other hand, the variation in measured emissions seem to correlate much better with $PM_{2.5}$. The fact that EC reacts differently from other pollutants is also obvious in the sections above where the measurement results for the individual boilers and stoves are presented.

This is in accordance with e.g. Savolahti et al., (2016) where it is stated that typically the share of BC increases along with combustion efficiency. A simplified explanation is that at inefficient combustion, condensable organic substances which contribute to the amount of $PM_{2.5}$ (and OC) are produced. Thus, at inefficent combustion $PM_{2.5}$ increases, resulting in a lower share of EC in $PM_{2.5}$.

Figure 14: Average of emissions from individual samples during the test cycles for traditional wood log boilers (P5–P6)

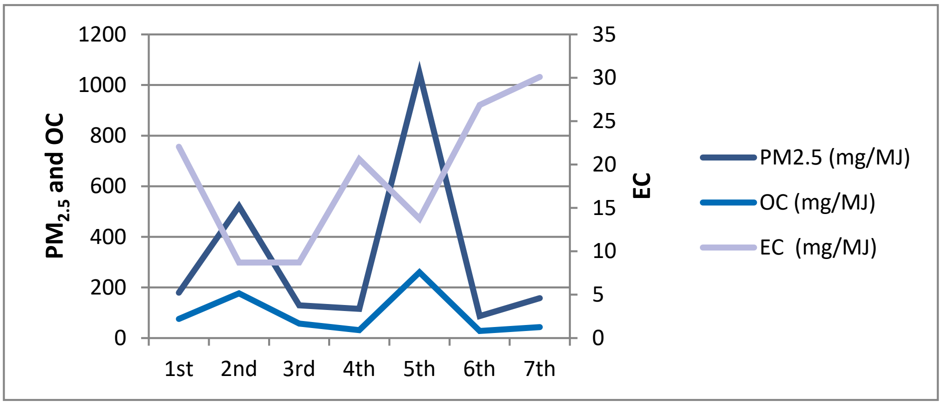
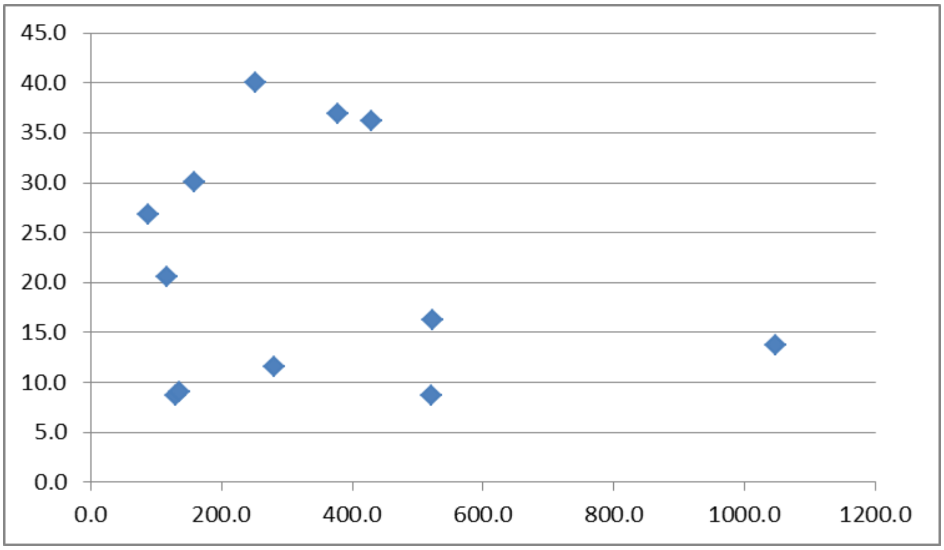


Figure 15 below shows results from individual samples from the traditional wood log boilers. The figure shows that there is no correlation between EC and $PM_{2.5}$.

Figure 15: Traditional log wood boilers. X=PM2.5, (mg/MJ), Y=EC (mg/MJ). All values are for nominal load and standard log wood



Similarly, there is no strong correlation between averaged values for EC and $PM_{2.5}$ emission factors between technologies, and between different operational conditions (Table 8). Calculated shares of EC/$PM_{2.5}$ are between 2% and 52%. Thus, expressing EC as a fraction of $PM_{2.5}$ emissions may not reflect the reality very well.

Table 8: EC as percentage of PM2.5 for boilers and stoves by technology and test conditions. Calculated from measurement result

$EC/PM_{2.5}$	Nominal load: Standard fuel	Nominal load: Moist fuel	Part load: Standard fuel
Modern log wood boilers	18%	8%	-
Traditional log wood boilers	7%	6%	2%
Pellet-fired boilers	17%	-	11%
Wood chip boilers	2%	-	3%
Modern stove	28%	2%	12%
State-of-the-art	3%	4%	5%
Older stove	9%	-	4%
Tiled and masonry stove	52%	9%	39%
Pellet stove	10%	-	5%
Sauna stove	50%	43%	-

3.7 Uncertainties

3.7.1 Overall variation between identical tests

Measurement data shows that the overall variation of emissions can be quite large even when firing takes place in a controlled environment and is carried out by experienced people. The variation in test results from three test cycles (of seven samples each) that were performed using the same combustion conditions and the same boiler (standard fuel moisture, nominal load and modern boiler P2) is presented in Figure 16.

Results for repeated, identical, test cycles (of three samples each) for the modern stoves A0 and A1 are presented in Figure 17 and Figure 18 (three tests for A0 and two tests for A1, nominal heat load, standard log wood).

It is obvious from the results that in most cases the results are rather similar, but also that the same lab can produce results with substantial variability when repeating the "same" measurement (e.g. NMVOC for boiler P2 and $PM_{2.5}$ for stove A0). This variation needs to be taken into consideration when using the measurement results in developing emission factors (i.e. not draw extensive conclusions from individual results).

Figure 16: Results from three repeated test cycles of seven samples each, and calculated averages. Boiler P2, nominal heat load and standard fuel (SLW)

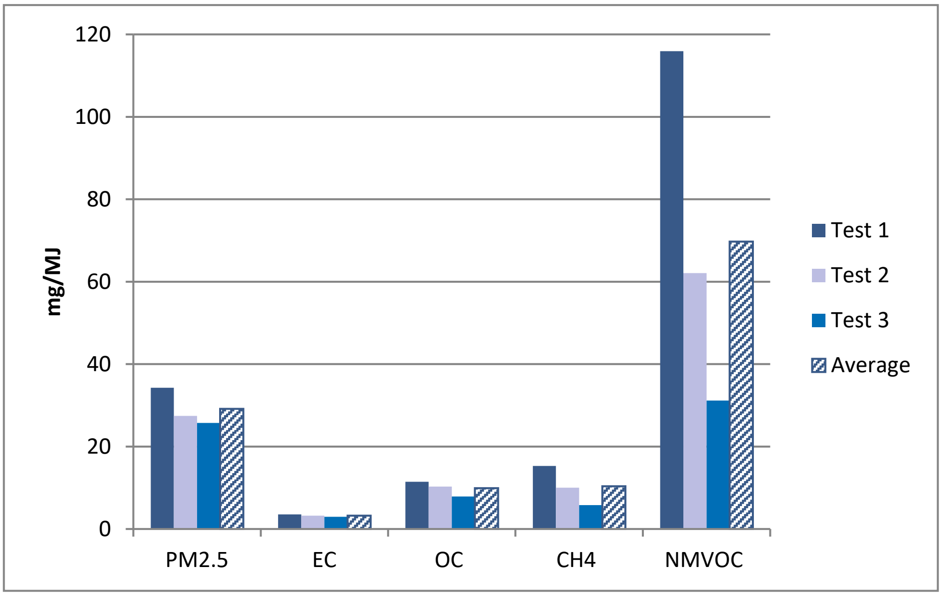


Figure 17: Results from three repeated test cycles of three samples each, and calculated averages. Stove A0, nominal heat load and standard fuel (SLW)

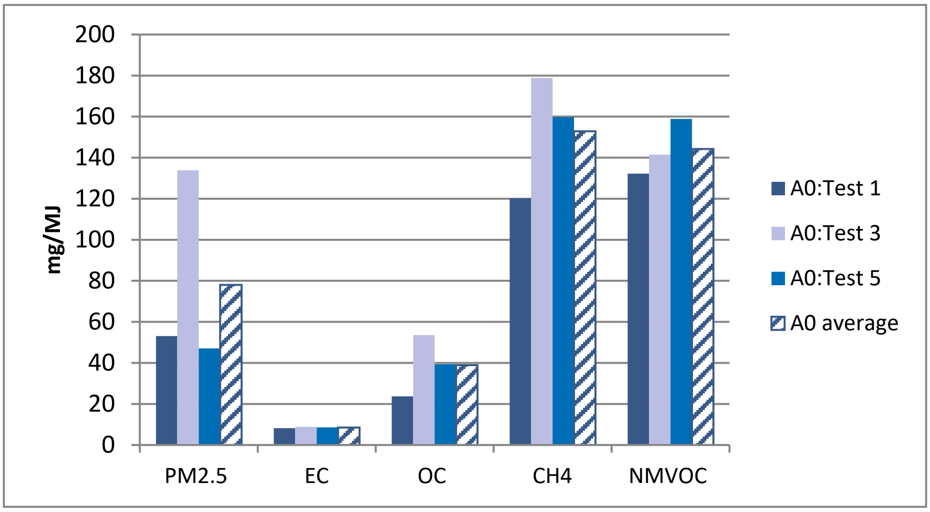
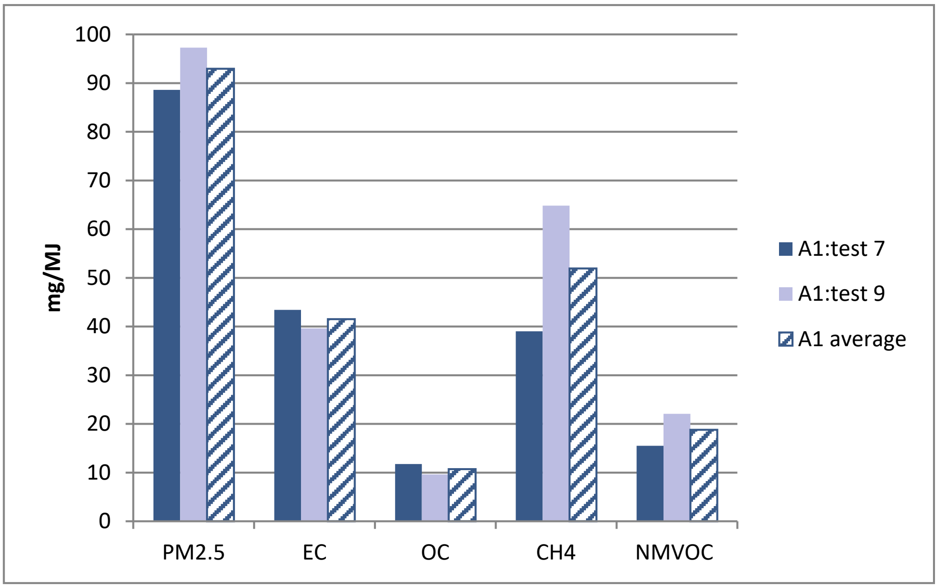


Figure 18: Two repeated test cycles of three samples each, and calculated average. Stove A1, nominal heat load and standard fuel (SLW)



From the results of the repeated identical tests presented in the figures above, the percentage differences to the calculated average is given in Table 9. The variation ranges from ± 5% up to as much as 70%. The numbers should be interpreted as an indication of possible uncertainties in the results from individual tests.

Table 9: Percentage difference in results from repeated identical tests to the average result. Number in parenthesis is the number of tests

	$PM_{2.5}$	EC	OC	CH_4	NMVOC
Boiler P2 (3)	+18%/-12%	+10%/-9%	+16%/-20	+48%/-44%	+66%/-55%
Stove A0 (3)	+72%/-40%/	+/-4%	+/-38%	+17%/-21%	+10%/-8%
Stove A1 (2)	+/-5%	+/-5%	+/-10%	+/-25%	+/-17%

As an example for general comparison; in a study to evaluate the total emissions and uncertainties of $PM_{2.5}$ from domestic wood combustion in Finland, Karvosenoja et al. (2008) estimated the $PM_{2.5}$ emission factor uncertainties to be in the range -54% to +88% (95% confidence interval). These uncertinty values were estimated primarily based on several sets of measurement data on stoves. The uncertainty range given by Karvosenoja et al., apart from variation in individual tests, also include uncertianties due to different stoves tested, varying maintenance, installation errors etc.

3.7.2 Uncertainties for $PM_{2.5}$

In the measurement program $PM_{2.5}$ was analysed by weighing the same quarts filters that were sampled for later analysis of EC and OC. Quarts filters are fragile and loss of filter material is difficult to avoid in the necessary handling during sampling and analysis. Furthermore, the sampling was optimised for subsequent EC/OC analysis. In several tests this led to too low loads of $PM_{2.5}$ on the filters for accurate determination by weighing. $PM_{2.5}$ emission levels of approximately 100 mg/MJ are reported in in Carlsson et al. (2016) to be somewhat of a lower limit for accurate results, when a stict uncertainty evaluation is made. Several of the results regarding $PM_{2.5}$ from the measurement program are lower than this value, which needs to be taken into consideration in developing emission factors for $PM_{2.5}$ based on these measurements.

On the other hand, the results regarding $PM_{2.5}$ are considered by the experienced labs performing the measurements to be well in line with previous measurements on comparable appliances of similar technologies. Thus, we choose to present the actual $PM_{2.5}$ results from the measurements, even if they are lower than 100 mg/MJ.

3.7.3 Other sources of uncertainty

Factors influencing the uncertainty in emission factors and emission estimates were discussed in the Background analysis (Kindbom et al. 2015). Some of the factors introducing uncertainties, such as different measurement standards and uncertainties concerning the influence of "bad" user practices have been considered in this measurement program. Thus, the measurement results are produced with harmonised test and analysis methods, and an attempt to take user practices into account was done by including test cases producing "bad combustion conditions" (i.e. moist fuel, part load).

Other sources of uncertainty include for example the impact on emissions from different fuel wood species, or the use of other fuels than clean wood. In addition, factors such as maintenance of the combustion equipment, installation errors, and non-optimised combinations of chimney and combustion appliance (influences the flue draft) impact the emissions. In terms of reducing emissions from residential wood burning, there is a growing awareness that the stove/boiler, the chimney and the user can be regarded as an interconnected system.

4. Emission measurement results by technology group

4.1 Grouping of technologies

In the work of preparing emission factors to be used in the national air emission inventories it is necessary to be able to match the emission factors to available activity data (technologies and fuels). The grouping proposed below is made based on similarities in technologies and emission levels measured in connection to this project, but also taking the variablility in measurement results for identical tests into account. The proposed technology groups for boilers are presented in Table 10 and for stoves in Table 11. In the tables the technologies included in each group are given, along with the number of tests performed for each group and test designation.

Table 10: Proposed technology groups and number of tests and samples for each group of boilers

Group	Load	Fuel quality	Number of tests	Number of samples/test	Boilers tested
Modern log wood boilers	Nominal	standard	6	7	P1x1, P2x3, P3x1, P4x1
Modern log wood boilers	Nominal	moist	3	7	P1, P2, P4
Modern log wood boilers	Nominal	dry	2	7	P2, P4
Traditional log wood boilers	Nominal	standard	2	7	P5, P6
Traditional log wood boilers	Nominal	moist	1	6	P5
Traditional log wood boilers	Part	standard	2	7	P5, P6
Traditional log wood boilers	Part	standard, small batches	1	7	P6
Pellet-fired boilers	Nominal	pellets	3	5	P7, P8, P9
Pellet-fired boilers	Part	pellets	3	5	P7, P8, P9
Wood chip boilers	Nominal	standard	1	5	P10
Wood chip boilers	Nominal	moist	1	4	P10
Wood chip boilers	Part	standard	1	6	P10
Wood chip boilers	Part	moist	1	4	P10

Table 11: Proposed technology groups and number of tests and samples for each group of stoves

Group	Load	Fuel quality	Number of tests	Number of samples/test	Room heaters tested
Modern stoves	Nominal	standard	7	3	A0x3, A1x2, A2x2
Modern stoves	Nominal	moist	2	3	A1, A2
Modern stoves	Nominal	dry	2	3	A1, A2
Modern stoves	Part	standard	6	2, 3	A0x3, A1, A2x2
Modern stoves	High	standard	2	3	A1, A2
Modern stoves	High	dry	1	3	A1
Modern stoves	NS3058	NS3058	2	3	A1, A2
State-of-the-art	Nominal	standard	1	3	A3
State-of-the-art	Nominal	moist	1	3	A3
State-of-the-art	Part	standard	1	2	A3
Older stove	Nominal	standard	1	3	A4
Older stove	Part	standard	1	2	A4
Tiled and masonry stove	Nominal	standard	2	3	A5, A6
Tiled and masonry stove	Nominal	moist	1	3	A6 (Masonry stove)
Tiled and masonry stove	Part	standard	1	2	A5 (Tiled stove)
Pellet stoves	Nominal	standard	1	3	A8
Pellet stoves	Part	standard	1	3	A8
Sauna stove	Nominal	standard	1	3	A9
Sauna stove	Nominal	moist	1	3	A9

4.2 Technology groups, boilers

For boilers the following technology groups are proposed in Carlsson et al. 2016:

- Modern log wood boilers (P1–P4)
- Traditional log wood boilers (P5, P6)
- Pellet fired boilers (P7–P9)
- Wood chip boiler (P10)

The reasoning behind the suggested practical grouping of technologies for national emission inventory purposes is given in Carlsson et al. 2016, and is as follows:

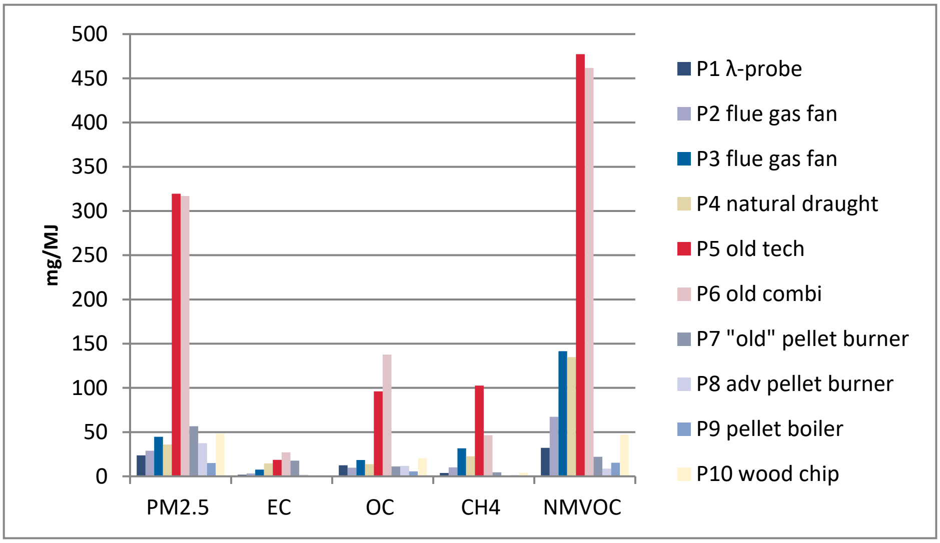
The modern log wood boilers P1–P4 are all boilers with modern combustion technology. i.e. with inverse combustion, ceramic insulated combustion chamber, in three cases a flue gas fan (P1, P2 and P3) and in one case also a λ-probe (P1) for excess air control. A flue gas fan leads to more stable combustion process. The boiler P4 has no flue gas fan but operates by natural draught.

Among the traditional wood log boilers, P5 is a boiler with simple combustion technology, and boiler P6 is an old combination boiler, i.e. a boiler intended for both wood and fuel oil firing. None of these two boilers have any of the features listed above.

For the pellet fired boilers a distinction could be made between P8 and P9 on the one hand, and P7, which is an old combination boiler in which a separate pellet burner is installed. P7 is originally not designed for pellet firing. This type of pellet boiler installation is the most common in Sweden. P8 and P9 on the other hand are boilers which are designed for pellet firing, where P8 has a separate advanced pellet burner installed and P9 has an integrated grate designed for pellet combustion. P10 is the only wood chip boiler.

The overall results from the individual boilers fired at nominal heat load and with standard log wood are presented in Figure 19 as an overview of the emission levels from the different technologies.

Figure 19: Emissions of PM2.5, EC, OC, CH4 and NMVOC for individual boilers, nominal heat load and standard fuel



Note: Modern boilers (P1–P4), Traditional boilers (P5–P6), Pellet boilers (P7–P9), Wood chip boiler (P10).

From Figure 19 it is evident that the traditional older technology boilers, P5 and P6, generally have the highest emission levels, why having them in one separate group is reasonable. The modern wood log boilers (P1–P4) show significantly lower emission levels than the old technologies. A separation of older technologies from modern technologies should be possible to obtain as activity data in a national inventory.

One group comprising pellet boilers is relevant. Pellet firing is possible to separate from other technologies in the national inventories since fuel statistics separating pellets from wood logs is usually available.

4.3 Measurement results by boiler technology group

The measured emissions for the technology groups for boilers are presented in Table 12 and in Figure 20. Results are given separately for the different test combinations of heat loads and fuel quality. This enables estimation of the degree of impact compared to the standard test case (nominal heat load and standard fuel). In Table 12 the ratio compared to nominal load and standard fuel (N:S) is calculated. In the table the number of test cycle results used for the reported data are indicated. Data for some groups are based on averages from several test cycles, while for some combinations of technology group and combustion condition there is only one test cycle making up the emission factor. The uncertainty in the results is of course higher if only one test cycle is available than if several test cycles are used as a basis for developing an emission factor.

Table 12: Emissions for boilers by technology group, and calculated ratio between test types. Numbers in parenthesis are the number test cycles. Interval, min–max given for the data. Ignition and pretest period are included in the data

	Nominal load: Standard fuel (N:S)	Nominal load: Moist fuel (N:M)	Nominal load: Dry fuel (N:D)	Part load: Standard fuel (P:S)	Part load: Moist fuel (P:M)	Ratio N:M/N:S	Ratio N:D/N:S	Ratio P:S/N:S
Modern log wood boilers	**(6)**	**(3)**	**(2)**					
$PM_{2.5}$ (mg/MJ)	32 (24–45)	43 (32–50)	61 (32–89)			1.3	1.9	
EC (mg/MJ)	6 (2–15)	4 (2–5)	6 (3–9)			0.6	1.1	
OC (mg/MJ)	12 (10–19)	12 (8–14)	24 (12–36)			0.9	1.9	
CH_4 (mg/MJ)	15 (4–32)	18 (2–35)	35 (8–62)			1.2	2.4	
NMVOC (mg/MJ)	86 (32–141)	124 (13–212)	168 (56–279)			1.4	2.0	
CO (mg/MJ)	1160 (233–2036)	1136 (178–1894)	1957 (754–3160)			1.0	1.7	
Traditional log wood boilers	**(2)**	**(1)**		**(3)**				
$PM_{2.5}$ (mg/MJ)	318 (317–320)	524		1162 (373–1975)		1.6		3.7
EC (mg/MJ)	23 (19–27)	>31		24 (15–35)		>1.3		1.0
OC (mg/MJ)	117 (96–138)	>143		461 (181–776)		>1.2		3.9
CH_4 (mg/MJ)	75 (47–103)	>28		158 (35–259)		>0.4		2.1
NMVOC (mg/MJ)	470 (462–477)	>272		>1059 (551–>1332)		>0.6		>2.3
CO (mg/MJ)	3271 (2963–3578)	4748		6274 (3437–8978)		1.5		1.9
Pellet-fired boilers	**(3)**			**(3)**				
$PM_{2.5}$ (mg/MJ)	36 (15–57)			96 (14–182)				2.6
EC (mg/MJ)	6 (1–14)			10 (6–17)				1.6
OC (mg/MJ)	10 (6–11)			34 (16–54)				3.5
CH_4 (mg/MJ)	2 (1–4)			11 (1–26)				5.1
NMVOC (mg/MJ)	15 (9–22)			95 (10–218)				6.2
CO (mg/MJ)	295 (120–631)			1249 (250–2273)				4.2
Wood chip boilers	**(1)**	**(1)**		**(1)**	**(1)**			
$PM_{2.5}$ (mg/MJ)	48	61		227	883	1.3		4.7
EC (mg/MJ)	1	6		7	16	4.8		6.0
OC (mg/MJ)	20	25		98	367	1.2		4.8
CH_4 (mg/MJ)	4	11		64	97	2.7		16.0
NMVOC (mg/MJ)	47	94		627	1160	2.0		13.3
CO (mg/MJ)	366	1894		4479	6780	5.2		12.2

For the modern log wood boilers the ratio of measured emissions between moist fuel and standard fuel roughly varies between 1–1.5. If fired with dry log wood emissions are generally twice as high as when fired with standard fuel (except for EC, where the ratio is close to 1.0). Thus, a factor for modern log wood boilers of 1.5–2 to take bad combustion conditions (unsuitable fuel quality) into consideration would be reasonable.

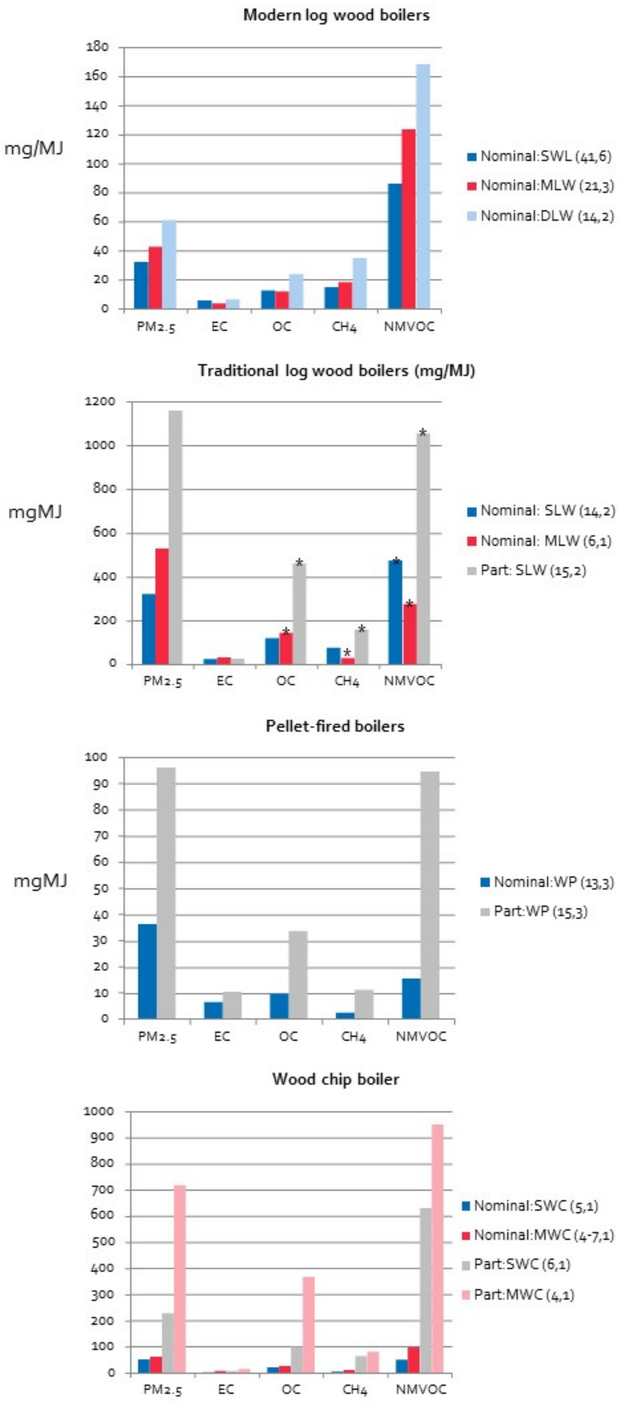
For the traditional log wood boilers several of the measurement results for moist fuel and part load firing were above the measurement range, and reported as "larger than" the given values. Moist fuel resulted in at least 1.5 times higher emissions than when using standard fuel. Comparing part heat load firing to nominal heat load firing gives a factor of 2–4 or higher emissions at part load conditions (except for EC).

Part heat load conditions in the pellet boilers resulted in emissions that were roughly 3–6 times higher than at nominal load (again, except for EC where the difference is smaller, ~1.5). The ratios were around 3 for $PM_{2.5}$ and OC, and the higher ratios (up to 6) for CH_4, NMVOC and CO.

The wood chip boiler seems very sensitive to part load firing, since the calculated ratio to nominal load firing is around 5 for the particulate matter compounds ($PM_{2.5}$, EC and OC), and as high as 12–16 for CH_4, NMVOC and CO.

Generally for the boilers, part load firing seem to have a larger impact on emission levels than using moist fuel.

Figure 20: Average emissions for boilers by technology group. Nominal and part heat load, standard (SLW/SWC) and moist fuel (MLW/MWC)



Note: *=actual value higher. Number in parenthesis=number of samples, number of test cycles.

4.4 Technology groups, stoves

For the stoves the following technology groups are proposed in Carlsson et al. 2016:

- Modern stoves (A0, A1, A2)
- State-of-the-art stove (A3)
- Older stove (A4)
- Tiled and masonry stove (A5–A6)
- Pellet stove (A8)
- Sauna stove (A9)

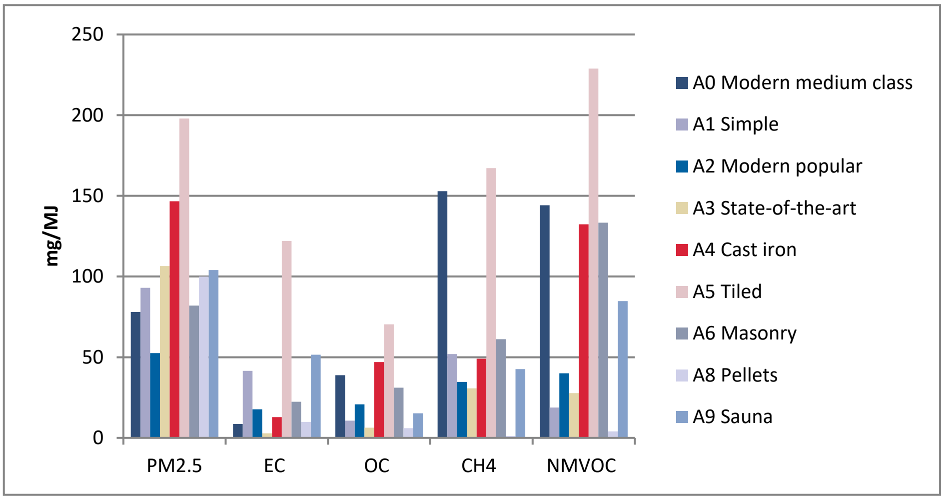
The reasoning behind the suggested grouping of technologies is given in Carlsson et al. 2016, and is as follows:

Among the tested stoves, A0, A1 and A2 all are modern stoves, basically having the same kind of air system with primary, secondary and tertiary air supply, and they can be regarded as a group in terms of expected emission levels. The A3 stove having automatic valve control and downdraft combustion in a dual firebox is a class of its own. The A4 stove is an older stove made of cast iron, so it is also a class of its own. The A5 and A6 stoves share quite a few characteristics, even though in age there are centuries between them. Both are masonry/tiled type of stoves having a comparatively basic air system and a long flue way before exit of the stove. They can be regarded as a group. Being a continuously fed pellet stove, the A8 stove is a class of its own, as is also the sauna stove A9 having a small firebox and a very basic air system.

The emission levels measured from the individual stoves at nominal load using standard fuel are presented for comparison in Figure 21. It is evident that the emission level differences are not as clear cut between the stoves as they were between different technology boilers.

It has been quite common to distinguish and to categorize stoves by age alone, but it is not as simple as that. Many other parameters like insulation of the firebox and the nature of the air system also influence expected emission levels, on which also the user has an impact.

Figure 21: Emissions of PM2.5, EC, OC, CH4 and NMVOC for stoves, nominal load and standard fuel. Modern stoves (A0–A2), State-of-the-art stove (A3), Older stove (A4), Tiled and masonry stove (A5–A6), Pellets stove (A8), Sauna stove (A9)



4.5 Measurement results by stove technology group

The measured emissions for the technology group modern stoves are presented in Table 13 and for all stove technology groups in Table 14 and in Figure 22. Results are given separately for the different test combinations of heat loads and fuel quality. This enables estimation of the degree of impact compared to the standard test case (nominal heat load and standard fuel). In the tables the ratio compared to Nominal load:Standard fuel (N:S) is calculated.

In the tables the number of test cycle results used for the reported data are indicated. Data for some groups are based on averages from several test cycles, while for some combinations of technology group and combustion condition there is only one test cycle making up the emission factor. The uncertainty in the results is of course higher if only one test cycle is available than if several test cycles are used as a basis for developing an emission factor.

The modern stoves were tested for the most combinations of combustion conditions. The sensitivity of stove performance to "bad combustion conditions", as represented by the part heat load and high heat load test cases, as well as moist fuel and dry fuel firing are presented for the group of modern stoves in Table 13.

Table 13: Emissions and ratios between test cases for the technology group Modern stoves (A0, A1 and A2). Numbers in parenthesis are the number of test cycles. Min–max given for the data

	Nominal load: Standard fuel (N:S)	Nominal load: Moist fuel (N:M)	Part load: Standard fuel (P:S)	Nominal load: Dry fuel (N:D)	High load: Standard fuel (H:S)	High load: Dry fuel (H:D)	NS3058
Modern stoves (A0,A1,A2)	**(7)**	**(2)**	**(4)**	**(2)**	**(2)**	**(1)**	**(2)**
$PM_{2.5}$ (mg/MJ)	74 (53–93)	584 (348–821)	154 (81–458)	111 (72–150)	171 (131–208)	287	388 (347–430)
EC (mg/MJ)	20 (9–42)	13 (9–18)	19 (6–27)	15 (10–19)	44 (n.a–44)	105	76 (31–120)
OC (mg/MJ)	26 (11–39)	263 (91–441)	62 (14–191)	16 (8–23)	49 (n.a.–49)	50	158 (149–167)
CH_4 (mg/MJ)	88 (35–153)	264 (160–368)	124 (67–245)	48 (37–59)	54 (35–72)	68	
NMVOC (mg/MJ)	77 (19–144)	519 (267–772)	158 (7–495)	16 (14–21)	66 (5–127)	87	
CO (mg/MJ)	1574 (1057–2287)	3458 (3078–3839)	2432 (1838–2730)	794 (656–931)	1206 (785–1628)	2223	
Modern stoves, ratio to N:S		**Ratio N:M/N:S**	**Ratio P:S/N:S**	**Ratio N:D/N:S**	**Ratio H:S/N:S**	**Ratio H:D/N:S**	**Ratio NS3058/ N:S**
$PM_{2.5}$ (mg/MJ)		7.9	2.1	1.5	2.3	3.9	5.2
EC (mg/MJ)		0.6	0.9	0.7	2.2	5.1	3.7
OC (mg/MJ)		10.2	2.4	0.2	2.0	1.9	6.1
CH_4 (mg/MJ)		3.0	1.4	0.4	0.6	0.8	-
NMVOC (mg/MJ)		6.8	2.1	0.2	0.9	1.1	-
CO (mg/MJ)		2.2	1.5	0.5	0.8	1.4	-

The modern stoves show high sensitivity to moist fuel (except for EC), where the ratio to standard fuel firing is 8–10 times for $PM_{2.5}$ and OC. NMVOC was around 7 times higher while CH_4 and CO were doubled. Notable though, is that especially one test cycle on one of the stoves produced very high emissions.

The high load test case with dry fuel produced high emissions of $PM_{2.5}$ and EC, around 4–5 times higher than nominal load and standard fuel. OC was doubled while the remaining pollutants were much less affected, resulting in emissions roughly on the same level as the standard case.

Part load and high load conditions, using standard fuel, both resulted in PM2.5 emissions 2–2.5 times higher than nominal load (except for EC at part load). Emissions of CH4, NMVOC and CO were increased by 1.5–2 times at part load, but were unaffected (or lower) at high load firing. Dry fuel at nominal heat load did not have a great effect on emissions.

In Table 14 emission factors for all groups of stoves are presented, including ratios of moist fuel to standard fuel, and of part heat load to nominal heat load. Here the state-of-the-art stove (A3) is included in the group of modern stoves. The reason for this is that the results for the state-of-the-art stove are based on only one test cycle. In addition, it is not reasonable to assume that this technology can be distinguished in national activity data collection.

Table 14: Emission factors and test case ratios for stove groups by technology. Numbers in parenthesis are the number of test cycles. Interval, min–max given for the data

	Nominal load: Standard fuel (N:S)	Nominal load: Moist fuel (N:M)	Part load: Standard fuel (P:S)	Ratio N:M/N:S	Ratio P:S/N:S
Modern stoves (incl. state-of-the-art)	**(8)**	**(3)**	**(5)**		
PM$_{2.5}$ (mg/MJ)	84 (53–106)	423 (100–821)	145 (74–458)	5.0	1.7
EC (mg/MJ)	20 (3–42)	10 (4–18)	14 (4–27)	0.5	0.7
OC (mg/MJ)	24 (6–39)	202 (25–441)	62 (7–191)	8.4	2.5
CH$_4$ (mg/MJ)	90 (31–153)	152 (80–368)	113 (11–245)	1.7	1.3
NMVOC (mg/MJ)	76 (19–144)	370 (71–772)	148 (1–495)	4.8	1.9
CO (mg/MJ)	1582 (919–2287)	2802 (1490–3839)	2406 (1386–3084)	1.8	1.5
Older stove	**(1)**		**(1)**		
PM$_{2.5}$ (mg/MJ)	147		330		2.2
EC (mg/MJ)	13		15		1.1
OC (mg/MJ)	47		155		3.3
CH$_4$ (mg/MJ)	49		140		2.9
NMVOC (mg/MJ)	132		322		2.4
CO (mg/MJ)	1165		2194		1.9
Tiled and masonry stove*	**(2)**	**(1)**	**(1)**		
PM$_{2.5}$ (mg/MJ)	140 (82–198)	78	285	0.6	2.0
EC (mg/MJ)	72 (22–122)	7	110	0.1	1.5
OC (mg/MJ)	51 (31–70)	24	100	0.5	2.0
CH$_4$ (mg/MJ)	114 (61–167)	49	204	0.4	1.8
NMVOC (mg/MJ)	181 (133–229)	75	154	0.4	0.9
CO (mg/MJ)	2365 (1585–3145)	1175	2751	0.5	1.2
Pellet stove	**(1)**		**(1)**		
PM$_{2.5}$ (mg/MJ)	100		153		1.5
EC (mg/MJ)	10		7		0.7
OC (mg/MJ)	6		3		0.4
CH$_4$ (mg/MJ)	1		3		2.6
NMVOC (mg/MJ)	4		14		3.3
CO (mg/MJ)	189		447		2.4
Sauna stove	**(1)**	**(1)**			
PM$_{2.5}$ (mg/MJ)	104	120		1.2	
EC (mg/MJ)	52	51		1.0	
OC (mg/MJ)	15	32		2.1	
CH$_4$ (mg/MJ)	43	80		1.9	
NMVOC (mg/MJ)	85	180		2.1	
CO (mg/MJ)	1405	2030		1.4	

Note: * Moist fuel was tested in the masonry stove, part load was tested in the tiled stove.

Part heat load firing in the older technology stove resulted in emissions that were 2–3 times that of nominal load firing (except for EC).

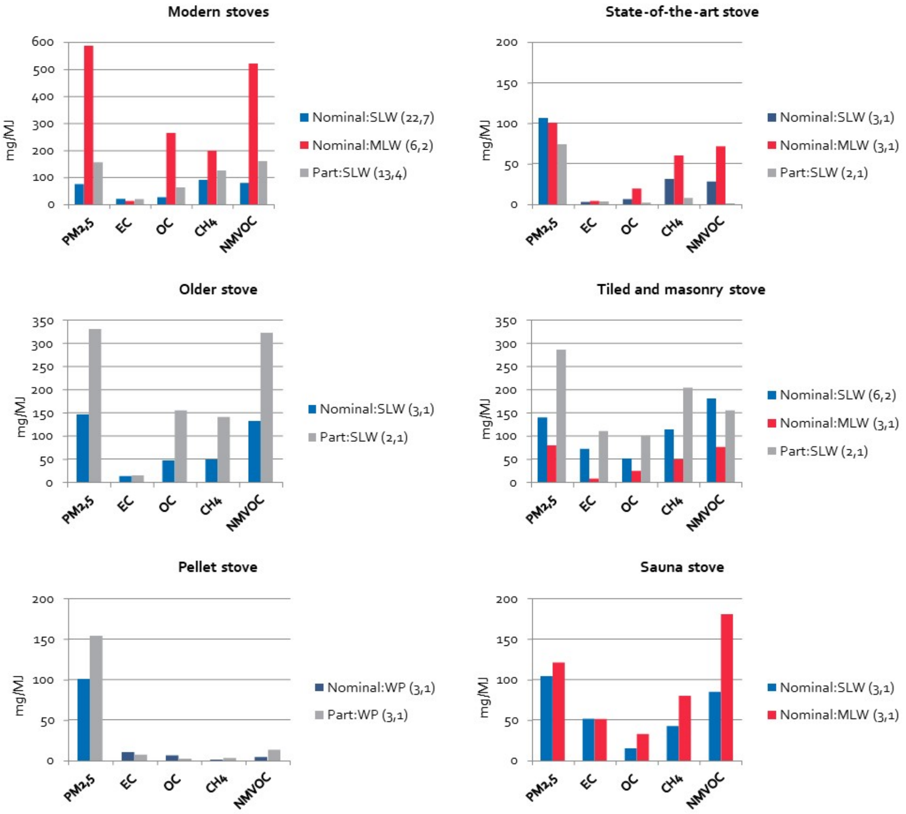
For the tiled stove part heat load increased the emissions up to two times, while moist fuel firing in the masonry stove did not.

The pellet stove showed $PM_{2.5}$, EC and OC emissions of rather similar levels as at nominal heat load firing, 1–1.5 times higher at part load, while CH_4, NMVOC and CO were 2.5–3 times higher.

The sauna stove when fired with moist fuel wood emitted $PM_{2.5}$ and EC of the same level as when using standard fuel wood, while emission levels of OC, CH_4 and NMVOC were approximately doubled.

The measurement results as averages for the defined groups of stoves are presented by technology group in Figure 22.

Figure 22: Average emissions by technology group of stoves. Emissions at nominal and part heat load, standard (SLW, WP) and moist fuel (MLW). Number in parenthesis=number of samples, number of test cycles



4.6 How to take the ignition phase into consideration

In the measurement program the ignition and start-up phase was sampled in all boiler tests and is included in the average emissions presented.

For the stoves only a few tests were done on the ignition phase. The results showed emissions that were higher than during the following test periods of normal firing, as presented in chapter 3.4 and in Table 15 below. The ratio of ignition to normal firing is in this case around 2 for $PM_{2.5}$, EC and NMVOC. For CH_4 and for CO the values are on the same level while the difference for OC is larger, almost 4 times higher at ignition.

Table 15: Emissions measured during the ignition phase (stove A2), at normal firing and calculated average for the whole test cycle. Ratio between emissions at ignition and at normal firing

	$PM_{2,5}$ (mg/MJ)	EC (mg/MJ)	OC (mg/MJ)	CH_4 (mg/MJ)	NMVOC (mg/MJ)	CO (mg/MJ)
Ignition	108	33	45	38	80	1082
Normal firing	53	16	12	34	32	1059
Average for whole test cycle	67	20	20	35	44	1065
Ratio, Ignition/normal firing	2.0	2.1	3.7	1.1	2.5	1.0

The test cycles for stoves in the test program normally consisted of three samples, excluding the ignition phase. The average emissions for a test cycle including ignition could thus be calculated assuming that the ignition contributes to one fourth of the time for the average of a total test cycle.

- $EF = (EF_{ign}+3*EF_{norm})/4$
- *where* $EF_{ign} = ratio_{ign/norm}*EF_{norm}$

If ignition is to be included in the emission factors, the example of $PM_{2.5}$ from the table above (using the ratio of 2 between ignition and normal firing) would be:

- $EF = (2*53+3*53)/4=66$

Emission factors calculated by the above method for modern stoves are presented in Table 16 for all pollutants except CH_4 and CO where the measured ratios were close to 1.0.

Table 16: Modern stoves: Calculated average emission factors without the ignition phase, and with ignition phase included. Based on ignition tests on one modern stove (stove A2)

	Nominal load: Standard fuel (N:S)	N:S including ignition
Modern stoves (incl state-of-the-art)	(8)	
$PM_{2.5}$ (mg/MJ)	84	105
EC (mg/MJ)	20	25
OC (mg/MJ)	24	41
NMVOC (mg/MJ)	76	96

The ignition and pre-test phase was not tested for the other stove technologies, but there is a general understanding that the ignition in most cases results in increased emission levels.

5. Emission factors

5.1 Emission factors and ratios for bad combustion conditions

Emission factors based on the results from the measurement program, including max and min test cycle values, are presented in Table 17 for boilers and in Table 18 for stoves. A more detailed discussion and evaluation of the results underlying the proposed emission factors and ratios for ”bad” combustion conditions is available in chapter 4.

The proposed emission factors are derived from test cases with nominal heat load conditions and standard fuel moisture. The tables also show the ratios derived for non-optimal combustion conditions. One ratio compares moist fuel to standard fuel at nominal heat load (N:M/N:S) for each technology group and pollutant, and the other compares part heat load to nominal heat load using standard fuel (P:S/N:S). The emission factors and ratios presented in Table 17 and table 18 are adjusted by rounding compared to the data presented in chapter 4. This was done in order to present the technology-specific levels of emission factors and ratios, and at the same time acknowledge measurement (and “real world”) variability.

The results indicate that boilers are more sensitive to part load conditions than to moist fuel (Table 17). For the technologies tested for both conditions (traditional log wood boilers and wood chip boiler) moist fuel increased e.g. the $PM_{2.5}$ emissions by 1.5 times, while part load increased the emissions by a factor of 4 and 5, respectively.

In general part load conditions increased the emissions from stoves by a factor of around 2 (Table 18). The modern stoves showed a high sensitivity to moist fuel, where e.g. the $PM_{2.5}$ emissions increased by a factor of 5, while part load doubled the emissions. The tiled and masonry stoves (air systems with larger capacity) were not sensitive to moist fuel, while also in this case, part load conditions increased the emissions of $PM_{2.5}$ by a factor of 2.

A brief comparison of the ratios found in the measurement program can be made with Finnish data used in the national emission inventory. The Finnish ratios are based on measurements. For $PM_{2.5}$ emissions a factor of 3 is used for moist fuel and a factor of 2 for part load. These ratios are applied for all wood log burning technologies in Finland, both boilers and stoves (UEF 2005, PUPO database).

Table 17: Emission factors for boilers (mg/MJ). Maximum and minimum values from measurements are given for nominal heat load and standard fuel

	Nominal load: Standard fuel (N:S)	*N:S min*	*N:S max*	Ratio moist fuel to standard fuel N:M/N:S	Ratio part load to nominal load P:S/N:S
Modern log wood boilers	(6)				
$PM_{2.5}$ (mg/MJ)	35	*24*	*45*	1.5	
EC (mg/MJ)	6	*2*	*15*	1.0	
OC (mg/MJ)	15	*10*	*19*	1.0	
CH_4 (mg/MJ)	15	*4*	*32*	1.5	
NMVOC (mg/MJ)	85	*32*	*141*	1.5	
CO (mg/MJ)	1160	*233*	*2037*	1.0	
Traditional log wood boilers	(2)				
$PM_{2.5}$ (mg/MJ)	320	*317*	*320*	1.5	4.0
EC (mg/MJ)	25	*19*	*27*	>1.5	1.0
OC (mg/MJ)	120	*96*	*138*	>1.5	>4.0
CH_4 (mg/MJ)	75	*47*	*103*	>1.5	>3.0
NMVOC (mg/MJ)	470	*462*	*477*	>1.5	>3.0
CO (mg/MJ)	3270	*2963*	*3578*	1.5	2.0
Pellet-fired boilers	(3)				
$PM_{2.5}$ (mg/MJ)	35	*15*	*57*		3.0
EC (mg/MJ)	6	*1*	*14*		1.5
OC (mg/MJ)	10	*6*	*11*		3.5
CH_4 (mg/MJ)	2	*1*	*4*		5.0
NMVOC (mg/MJ)	15	*9*	*22*		6.0
CO (mg/MJ)	295	*120*	*631*		4.0
Wood chip boiler*	(1)				
$PM_{2.5}$ (mg/MJ)	50			1.5	5.0
EC (mg/MJ)	2			5.0	6.0
OC (mg/MJ)	20			1.5	5.0
CH_4 (mg/MJ)	5			3.0	15.0
NMVOC (mg/MJ)	50			2.0	15.0
CO (mg/MJ)	366			5.0	12.0

Note: The last two columns show the ratio of moist fuel to standard fuel at nominal heat load (N:M/N:S) and the ratio of part load to nominal load using standard fuel (P:S/N:S). Numbers in parenthesis are number of test cycles.

* Data based on only one test cycle.

Table 18: Emission factors for stoves (mg/MJ). Maximum and minimum values from measurements are given for nominal heat load and standard fuel. One column shows the emission factors taking ignition into consideration for modern stoves

	Nominal load: Standard fuel	*N:S min*	*N:S max*	N:S including ignition	N:M/N:S	P:S/N:S
Modern stoves (incl state-of-the-art)	**(8)**					
$PM_{2.5}$ (mg/MJ)	84	*53*	*106*	105	5.0	2.0
EC (mg/MJ)	20	*3*	*42*	25	1.0	1.0
OC (mg/MJ)	24	*6*	*39*	41	8.0	2.5
CH_4 (mg/MJ)	90	*31*	*153*	90	2.0	1.5
NMVOC (mg/MJ)	76	*19*	*144*	96	5.0	2.0
CO (mg/MJ)	1582	*919*	*2287*	1582	2.0	1.5
Older stove*	**(1)**					
$PM_{2.5}$ (mg/MJ)	147					2.5
EC (mg/MJ)	13					1.0
OC (mg/MJ)	47					3.5
CH_4 (mg/MJ)	49					3.0
NMVOC (mg/MJ)	132					2.5
CO (mg/MJ)	1165					2.0
Tiled and masonry stove**	**(2)**					
$PM_{2.5}$ (mg/MJ)	140	*82*	*198*		1.0	2.0
EC (mg/MJ)	72	*22*	*122*		1.0	1.5
OC (mg/MJ)	51	*31*	*70*		1.0	2.0
CH_4 (mg/MJ)	114	*61*	*167*		1.0	2.0
NMVOC (mg/MJ)	181	*133*	*229*		1.0	1.0
CO (mg/MJ)	2365	*1585*	*3145*		1.0	1.0
Pellet stove*	**(1)**					
$PM_{2.5}$ (mg/MJ)	100					1.5
EC (mg/MJ)	10					1.0
OC (mg/MJ)	6					1.0
CH_4 (mg/MJ)	1					2.5
NMVOC (mg/MJ)	4					3.5
CO (mg/MJ)	189					2.5
Sauna stove*	**(1)**					
$PM_{2.5}$ (mg/MJ)	104				1.5	
EC (mg/MJ)	52				1.0	
OC (mg/MJ)	15				2.0	
CH_4 (mg/MJ)	43				2.0	
NMVOC (mg/MJ)	85				2.0	
CO (mg/MJ)	1405				1.5	

Note: The last two columns show the ratio of moist fuel to standard fuel at nominal heat load (N:M/N:S) and the ratio of part load to nominal load using standard fuel (P:S/N:S). Numbers in parenthesis are number of test cycles.

* Data based on only one test cycle.

** Moist fuel was tested in the masonry stove, while part load was tested in the tiled stove see Table 6.

5.2 How to take bad combustion conditions into consideration in the emission factors

To estimate emissions from a specific source, the following simple equation is used:

- Emissions = AD * EF

where:

- AD = fuel use in the specific technology or technology group (MJ)
- EF = emission factor for a pollutant (mg/MJ)

If bad combustion conditions are to be taken into consideration in the emission factor (EF), the equation below can be used (Savolahti et al., 2016):

- $EF = EF_{Normal} * S_{Normal} + Ratio_{Bad/Good} * EF_{Normal} * S_{Bad}$

where:

- EF_{Normal} = Emissions under normal combustion conditions;
- S_{Normal} = Share of fuel used in the specific technology burned under *normal* combustion conditions. For example, if normal combustion conditions is assumed to occur for 80% of the total fuel use in the technology, the share would be 0.8;
- $Ratio_{BadGood}$ = Factor telling how many times the emissions are higher under bad combustion conditions than under normal combustion conditions. For instance, if the emissions are three times higher during bad combustion conditions the ratio would be 3;
- S_{Bad} = Share of fuel used in the specific technology burned under bad combustion conditions ($S_{Bad} = 1 - S_{Normal}$), e.g if the normal combustion share is 0.8, the bad combustion share will be 0.2 (1–0.8 = 0.2).

Ratios between normal and bad combustion conditions can be derived from the measurement program results (Table 17 for boilers and Table 18 for stoves). From the measurement program there are separate factors for the two different "bad combustion conditions" of part load firing and use of moist fuel. The emission factor, taking moist fuel and part load into account separately would be calculated as follows:

- $EF=(EF_{Normal}*S_{Normal})+(Ratio_{Moist/Standard}*EF_{Normal}*S_{Moist})+(Ratio_{Part/Nominal}*EF_{Normal}*S_{Part})$

Usually this kind of detailed information is not available. The shares of normal or bad combustion conditions need to be assumed, and can be based on expert estimates, on studies, interviews with chimney sweepers etc.

5.2.1 *Example calculation including assumptions on "bad combustion conditions"*

We assume, for example, that for traditional log wood boilers 70% of the fuel is combusted under normal conditions (nominal load, standard fuel), 5% of the fuel is moist and the remaining amount of fuel, 25%, is fired at part load. The emission factor for $PM_{2.5}$ would be calculated as follows (using the equation above):

- $EF_{PM2.5}=(320*0.7)+(1.5*320*0.05)+(4*320*0.25)=568$ mg/MJ

where:

- $EF_{Normal} = 320$
- $S_{Normal}=0.7$
- $Ratio_{Moist/Standard}= 1.5$
- $S_{Moist} = 0.05$
- $Ratio_{Part/Nominal} = 4$
- $S_{Part} = 0.25$

Thus, the emission factor for $PM_{2.5}$ with the assumed shares of moist fuel and part load firing respectively, would be 568 mg/MJ instead of 320 mg/MJ under nominal load and standard fuel conditions (Table 19).

Table 19: Example calculation of emission factors (EF, mg/MJ) including bad combustion conditions where it is assumed that 70% is combusted under normal conditions (N:S), 5% use moist fuel and 25% is fired at part load

Traditional log wood boilers	EF N:S mg/MJ	ratio M/S Moist fuel / Standard fuel	ratio P/N Part load / Nominal load	Emission factors, including "bad combustion" according to example assumptions
$PM_{2.5}$	320	1.5	4	568
EC	25	1.5	1	26
OC	120	1.5	4	213
CH_4	75	1.5	3	114
NMVOC	470	1.5	3	717
CO	3270	1.5	2	4169

5.3 Comparison with literature and current national emission factors

The EMEP/EEA Air Pollutant Emission Inventory Guidebook (2016) includes default emission factors for a number of different residential wood burning technologies. The technology groups in the EMEP/EEA Guidebook are not always directly comparable to the ones in this project. Comparisons in Table 20 – Table 27 are between the technology groups from the Guidebook and from this project that are judged to be the most similar. The emission factors for advanced/eco-labelled stoves and boilers in the EMEP/EEA Guidebook are listed together and are hence identical.

In the tables the default emission factors from the EMEP/EEA Guidebook and current ranges of region-and technology specific emission factors for $PM_{2.5}$, BC and OC in the GAINS model (Klimont et al., 2016) are compared to the proposed emission factors for nominal load and standard fuel conditions from this project. Also the current emission factors used in the Nordic countries are listed in the tables. The emission factors in the Nordic countries have different levels of technology differentiation (Kindbom et al. 2015), from a few technologies to very detailed differentiation.

In Iceland, emissions from residential biomass combustion have not been estimated as of today and no emission factors have therefore been used. In contrast to other Nordic countries, the great majority of residences uses either (geothermal) district- or electric heating (around 90% geothermal and 10% electricity), suggesting a much lower impact of residential combustion of biomass on total national SLCP emissions than in the other Nordic countries. Use of wood stoves in residences in Iceland is not common and usually only fired up for pleasure and coziness. A small part of summerhouses in Iceland use biomass as the main source for heating only for a few weeks per year. In addition, the small population of Iceland compared to other Nordic countries suggests, overall, a very small impact of the Icelandic residential combustion of biomass on total Nordic SLCP emissions.

Even though the emission factors compared in the tables below do not always refer to exactly the same technology, it is obvious that there are sometimes large differences. This applies both when comparing the default factors from the EMEP/EEA Guidebook to the emission factors developed in this project, as well as in relation to the national emission factors. In general, the emission factors developed in this project (nominal load and standard fuel, N:S) tend to be on the lower side compared to the default factors in the EMEP/EEA Guidebook, with the exception of pellet fired boilers and stoves. If "bad combustion condition" ratios measured in this project (Table 17 and Table 18) would be weighted into the emission factors, they would be higher. How much higher depends on the extent of "bad combustion". Most of the emission factors developed in this project, however, lie within the 95% confidence intervals given in the EMEP/EEA Guidebook (Table 20 – Table 27).

Table 20 – Table 27: Comparison of default emission factors from EMEP/EEA Guidebook (mg/MJ, and lower and upper 95% confidence interval, for BC also % of PM2.5 is given), GAINS current ranges of region- and technology specific emission factors (Klimont et al., 2016), results from this project (nominal load and standard fuel, N:S min–max), and national emission factors for comparable technologies (mg/MJ). NA=not available.

Table 20: EMEP/EEA: Advanced/ecolabelled boilers. This project:Modern boilers

	EMEP/EEA	GAINS$	This project N:S	Denmark	Finland**	Norway*	Sweden#
$PM_{2.5}$	93 (19–233)	80–520 / 40–260	35 (24–45)	206–413	17/115	146	150
BC/EC	26	32-50 / 13-37	6 (2-15)	58–116	0.5/24	24	24
BC, % of PM2.5	28% (11-39%)						
OC	NA	22–230 / 12–100	15 (10–19)	NA	NA	15	NA
CH_4	NA		15 (4–32)	50	50/200	11	254
NMVOC	250 (20–500)		85 (32–141)	175	49	75	300

Note: *Norway and Sweden, same as conventional boiler.
** Finland: Manually fed modern/manually fed with accumulator tank.
$ Improved/new modern.
# Swedish emission factors are based on hot flue gas measuerements.

Table 21: EMEP/EEA: Conventional boilers. This project: Traditional boilers

	EMEP/EEA	GAINS**	This project N:S	Denmark	Finland	Norway	Sweden
$PM_{2.5}$	470 (235–940)	230–1300	320 (317–320)	900–1800	135–700	146	150
BC/EC	75	75–200	25 (19-27)	144–288*	24–210	24	24
BC, % of $PM2.5_5$	16% (5–30%)						
OC	NA	75–600	120 (96–138)	NA	NA	15	NA
CH_4	NA		75 (47–103)	211–256	50–200	11	254
NMVOC	350 (100–2000)		470 (>462–477)	350	49–402	75	300

Note: * BC calculated as % of PM2.5 as given in the EMEP/EEA Guidebook (2016).
** Old uncontrolled boiler.

Table 22: EMEP/EEA and This project: Pellet boilers

	EMEP/EEA	GAINS	This project N:S	Denmark	Finland	Norway*	SINTEF 2016**	Sweden
$PM_{2.5}$	29 (9–47)	20–68	35 (15–57)	29	20	146	150	30
BC/EC	4.4	5	6 (1–14)	4.4	0.5	24		4.5
BC, % of PM2.5	15% (6–39%)							
OC	NA	2.5–10	10 (6–11)	NA	NA	15		NA
CH_4	NA		2 (1–4)	3	50–200	11	15	3
NMVOC	10 (1–30)		15 (9–22)	10	3	75	77	6

Note: * Norway, same as conventional boiler.
**Suggested new emission factors for Norway.

Table 23: This project: Wood chip boiler

	EMEP/EEA	This project N:S	Finland (automatic)	Norway (briquets)	Sweden
$PM_{2.5}$	NA	*50*	16	146	100
BC/EC	NA	*5*	0.5	24	16
OC	NA	*20*	NA	15	NA
CH_4	NA	*5*	50–200	11	203
NMVOC	NA	*50*	3	75	150

Table 24: EMEP/EEA: Advanced/ecolabelled stoves. This project: Modern stoves

	EMEP/EEA	GAINS$	This project, N:S	Denmark	Finland	Norway part load*	Norway nominal load*	Sweden**
$PM_{2.5}$	93 (19–233)	30–186	84 (53–106)	155	72	758	690	100
BC/EC	26	9–30	20 (3–42)	43	17	51	54	10
BC, % of PM2.5	28% (11–39%)							
OC	NA	8–67	24 (6–39)	NA	NA	623	551	NA
CH_4	NA		90 (31–153)	2	50–200	732	732	430
NMVOC	250 (20–500)		76 (19–144)	175	82	417	417	150

Note: * Norway, stove produced after 1998. Emission factors for PM2.5, EC and OC derived using NS3058.
** Sweden, same as for conventional stove.
$ New wood stove.

Table 25: EMEP/EEA: Energy efficient stoves. This project: Tiled and masonry stoves

	EMEP/EEA	GAINS$	This project N:S	Denmark	Finland$$	Norway*	Sweden**
$PM_{2.5}$	370 (285–740)	55–372	140 (82–198)	257	33–138		100
BC/EC	59	30–95	72 (22–122)	41	15–47		10
BC, % of PM2.5	16% (5–30%)						
OC	NA	11–133	51 (31–70)	NA	7–25		NA
CH_4	NA		114 (61–167)	125	45–200		430
NMVOC	350 (100–2000)		181 (133–229)	350	106–209		150

Note: *Norway, emission factor is based on the age of the stove.
**Sweden, same as for conventional stove.
$ Improved wood stove.
$$ Finnish masonry stoves.

Table 26: EMEP/EEA: Conventional stoves. This project: Older stove

	EMEP/EEA	GAINS	This project N:S	Denmark	Finland	Norway part load*	Norway nominal load*	Sweden
$PM_{2.5}$	740 (370–1480)	150–930	147	740	113	1284	984	100
BC/EC	74	32–100	13	74	27	57	60	10
BC, % of PM2.5	10% (2–20%)							
OC	NA	60–435	47	NA	NA	996	767	NA
CH_4	NA		49	430	50–200	732	732	430
NMVOC	600 (20–3000)		132	600	92–3984	417	417	150

Note: *Norway, stove produced before 1998. Emission factors for PM2.5, EC and OC derived using Norwegian standard (NS3058).

Table 27: EMEP/EEA and This project: Pellet stoves

	EMEP/EEA	GAINS	This project N:S	Denmark	Finland	Norway	SINTEF 2016*	Sweden
$PM_{2.5}$	29 (9–47)	10–47	100	29	NA	64	150	30
BC/EC	4.4	1.3–4	10	4	NA	2		4.5
BC, % of PM2.5	15% (6–39%)							
OC	NA	2–7	6	NA	NA	11		NA
CH_4	NA		1	3	NA	300	15	7
NMVOC	10 (1–30)		4	10	NA	376	77	6

Note: * Suggested new emission factors for Norway.

The national emission factors show large variations for similar technologies. For example, for several log wood burning technologies (both boilers and stoves) the emission factors for $PM_{2.5}$ and EC are considerably higher in Denmark than in Finland or Sweden. The Swedish emission factors are based on hot flue gas measurements while for Norway, the high emission factors for $PM_{2.5}$, EC and OC for stoves are derived using the Norwegian standard. These factors are thus not directly comparable to other data (e.g. the emission factors developed in this project), but are the ones used in the national Swedish and Norwegian emission inventories. In the Swedish inventory there is also no differentiation between modern and older technology wood boilers or wood stoves.

In the current national inventories, specific assumptions on bad combustion conditions are only used in Norway and Finland. In Norway different emission factors are used for wood burnt in stoves in urban areas compared to in the rest of the country, while in Finland emission factors are weighted taking "bad combustion" into consideration. The Finnish method is very similar to the one proposed in this report, but using country specific shares and factors for "bad combustion".

In Denmark and Sweden, the national emission factors are assumed to be weighted to include "bad combustion" and represent the national conditions, but no specific shares are currently used in the inventory calculations.

In Table 28 emission measurement results from this project are briefly compared to published data in Klimont et al. (2016), Savolahti et al. (2016) and in Andersen & Hvidberg (2017). The ranges in the table may represent different types of combustion conditions, from nominal conditions to various types of "bad" combustion conditions.

In Klimont et al. (2016) a literature review and summary of published emission factors for particulate matter is available. Savolahti et al. (2016) present emission factors for $PM_{2.5}$ and BC for residential wood combustion appliances common in Finland. Most of the emission factors are equal to or very similar to those presented as Finnish national emission factors in Table 20 – Table 27, but there is a higher technology differentiation and more appliance types are included in Savolahti et al. There is for example information for conventional and for modern masonry heaters, as well as for conventional and modern sauna stoves (see Table 28). In a recent measurement campaign in Denmark (Andersen & Hvidberg, 2017) four different modern stoves (from 2010–2014) were fired under different operational conditions. Two of the tested parameters were the influence on PM emission levels from fuel moisture and from using too much wood and at the same time reducing the air supply.

The comparison of measurement results from this project and literature data in Table 28 show that the ranges may be rather wide, and that combustion conditions certainly influence emissions. The emission factors and ranges summarised in Klimont et al. (2016), in Savolahti et al. (2016) and in Andersen & Hvidberg (2017) are largely comparable to the results in this project.

Table 28: Comparison of emissions measurement results in this project and literature (mg/MJ). When ranges are given, they may include different types of combustion conditions, both normal and "bad" conditions

Technology	Pollutant	This project*	Literature	Reference
Older/traditional wood boilers	$PM_{2.5}$	317–1975	95–1300 (73–2200)**	Klimont et al. 2016
Moder wood boilers	$PM_{2.5}$	24–89	44 (11–450)**	Klimont et al. 2016
Conventional/traditional wood stove	$PM_{2.5}$	78–330	90 – 3000	Klimont et al. 2016
-"-	BC/EC	7–122	20–72	Klimont et al. 2016
-"-	OC	22–127	70–623	Klimont et al. 2016
Modern wood stoves	$PM_{2.5}$ / PM	53–821	36–798	Andersen & Hvidberg, 2017
New/improved/modern wood stove	$PM_{2.5}$	53–821	22–350	Klimont et al. 2016
-"-	BC/EC	3–104	9–88	Klimont et al. 2016
-"-	OC	6–441	11–67	Klimont et al. 2016
Masonry heater	$PM_{2.5}$	78–82	93 (19–311) conventional. 33 (23–67) modern	Savolahti et al. 2016
-"-	EC / BC	7–22	38 (6–96) conventional 15 (8–55) modern	Savolahti et al. 2016
Sauna stove	$PM_{2.5}$	104–120 (modern)	389 (35–1567) conventional Modern, 50% of conventional	Savolahti et al. 2016
-"-	EC / BC	18–28 (modern)	173 (7–330) conventional Modern, 50% of conventional	Savolahti et al. 2016

Note: *Min and max, including all combustion conditions tested.
** Min and max in parenthesis.

In Savolahti et al. (2016) and in Andersen & Hvidberg, (2017) separate factors for "bad combustion" in wood stoves are presented. Savolahti et al. present factors for smoldering combustion conditions in stoves, where the factors are between 2 to approximately 5 times higher than at normal combustion depending on combustion technology. According to Andersen & Hvidberg, (2017) moist wood increases emissions, and also that the emissions of particles could increase by a factor of 2–3 if the stove is loaded with too much wood and with a reduced air supply. These factors are in line with the factors for "bad combustion" derived from measurements in this project (Table 18).

5.4 Factors affecting combustion conditions

The emission factors presented in chapter 5.1 are a basis for developing "real life" factors by assessing and weighing the degree of bad combustion conditions into the basic emission factor derived from nominal heat load and standard fuel conditions. The ratios for "bad combustion" presented in chapter 5.1 are derived from measurements using moist fuel, and from firing at part load (underloading). These are some typical "user mistakes" that increases emissions, but there are also other factors that should be contemplated on when developing national emission factors.

There is no single condition such as "real life operating conditions". On the contrary there are a number of combinations impacting emission levels, including properties of the stove, properties of the house and its chimney, variation in climatic conditions (even within Scandinavia), variation in stove type, variable quality of the firewood used and perhaps most important of all, the knowlegde of the user. Several of those variables have been taken into consideration in this project, such as the quality of the firewood (dry, standard or moist fuel), overloading (high load) or underloading (part load) the stove/boiler, various valve settings (the tests according to Norwegian standard). Therefore these results are deemed adequately diverse, to allow composition of emission factors for national air emission inventories.

Some factors that are influenced by the user and have an impact on emissions from residential wood combustion are summarised in Table 29.

Table 29: Summary of user influenced factors and their general impact on emissions from residential wood burning, compared to cases with nominal load and standard fuel

Factor	General influence on emissions
Moist firewood	Increases
Overloading by 150% or more	Increases
Underloading (part load)	Increases
Smoldering combustion	Increases
Poor maintenance of equipment	Increases
Installation error	Increases
Moderately dry firewood	Neutral
Efficienct combustion, proper control of air supply	Neutral
Increased flue draft	Decreases
Small log size	Decreases
Upright arrangement of wood logs	Decreases
Ignition from the top	Decreases

In the annex, impacts on emissions arising from operation and the status of maintenance of equipment, from the fuel quality, from user influence during firing, and from the variations in air supply during combustion are discussed in more detail.

Conclusions

In order to improve the national emission inventories of SLCP, and reduce uncertainties, a better understanding of emission factors is essential. Apart from emission factors, also national activity data on technologies, fuel consumption and combustion conditions are important. This project contributes to a better knowledge base for emission factors for $PM_{2.5}$, EC, OC, CH_4, NMVOC and CO from residential wood burning, as well as ratios for increased emissions at "bad combustion conditions". Bad combustion conditions can be weighted into the national emission factors, depending on national circumstances.

Among the tested boilers, the traditional wood log boilers exhibited the highest emission factors, generally in the order of 5–10 times higher (depending on pollutant) than the modern boilers, the pellet boilers and the wood chip boiler, which were rather comparable. Part load combustion conditions increased the emissions between 2–6 times (or even higher), depending on pollutant and technology, while moist fuel generally increased emissions approximately by a factor of 1.5–2.

Among the stoves the difference in emission factors between technologies were not as pronounced as for the boilers. The highest emission factors were measured from the tiled stoves, followed by the older stove. In comparison to the modern stoves and the sauna stove the emission factors were generally in the order of 1.5–2 times higher from the older/traditional technologies. The pellet stove showed very low emission factors for most pollutants.

Moist fuel had a large effect on $PM_{2.5}$ and OC emission levels for the modern stoves, 5–8 times, while the emission levels were in principle unaffected by moist fuel combustion in the tiled and masonry stoves. The higher impact from moist fuel in the modern stoves is probably mainly due to limited capacity of the air systems among many modern stoves compared to the older technologies. For the stoves, part load combustion generally increased emissions by 1.5 up to 3.5 times.

Both for the boilers and the stoves the EC emission factors did not correlate with the emission factors for $PM_{2.5}$. Also, the EC emissions were less affected by moist fuel and part load conditions than most of the other pollutants.

To improve the national emission inventories of SLCPs the large sensitivity to operational conditions (moist fuel and part load) needs to be taken into consideration in national emission inventories, where "real life" emissions are estimated. Country-specific assessments on shares of "bad combustion conditions" are essential to properly weigh bad combustion into the national emission factors.

The measurement results from this project provides a comparison to the default emission factors in the EMEP/EEA Air Emission Inventory Guidebook. The emission factors developed for the wood log boilers (both modern and traditional), as well as for the older technology stoves (older stove, tiled and masonry stoves), are lower than the default emission factors given in the EMEP/EEA Air Emission Inventory Guidebook. This refers to the emission factors derived from standard operational conditions (nominal load and standard fuel), not taking into account "bad combustion conditions", which would normally increase the emission factor levels. For the other technologies, the levels are in general more comparable, given that the definitions of technologies do not always match.

When comparing currently used national emission factors in the Nordic countries with those developed from the measurement program in this project, it is obvious that there are sometimes large differences, both between countries and in relation to the measurement results. Individual national emission factors are both considerably higher, or considerably lower, than the measurement results.

The comparison highlights discrepancies in the emission factors between the Nordic countries. Some of the differences between current national factors are due to that they are based on measurement results derived using different measurement standards (e.g. hot flue gases/diluted sampling, or EN standards/Norwegian standard). In order for national emission inventory results to be comparable, a harmonisation of emission factor levels is needed, unless there are real differences between the countries. The results from this project provides additional knowledge for developing emission inventories that are more comparable between the Nordic countries.

The measurement results and the emission factors developed in this work increases the knowledge base for estimating emissions of SLCPs (and $PM_{2.5}$) with less uncertainties in the future. However, the measurement program also showed that there can be quite a large variabilty when repeating identical test cases, why additional well designed measurements would add information that can be used for refining the emission factors to reflect reality with higher certainty.

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Sammanfattning

Den övergripande målsättningen för detta projekt är att förbättra de nordiska ländernas emissionsinventeringarna av kortlivade klimatpåverkande luftföroreningar (Short-Lived Climate Pollutants, SLCP). Som ett första steg i projektet genomfördes och rapporterades en bakgrundsanalys (Kindbom m.fl., 2015). Där summeras nuvarande rapporterade emissionsnivåer och status för de nordiska emissionsinventeringarna. Rapporten lägger också grunden för det mätprogram som genomförts och rapporteras i detta andra steg av projektet.

För att minska osäkerheterna och förbättra de nationella nordiska emissionsinventeringarna av SLCP är det viktigt med en bättre förståelse för emissionsfaktorer vid utsläpp till luft från småskalig biomassaförbränning. Förutom emissionsfaktorer är även förbättrad kunskap om aktivitetsdata viktigt, d.v.s. vilka teknologier som används, deras bränsleförbrukning och vilka förbränningsförhållanden som råder. Förbättring av aktivitesdata har inte studerats i projektet..

De genomförda emissionsmätningarna bidrar till en bättre kunskap om emissionsfaktorer till luft för $PM_{2.5}$, EC, OC, CH_4, NMVOC och CO från småskalig biomassaförbränning. Genom att även mäta vid icke optimala förbränningsförhållanden har faktorer för ökade emissioner vid ”dålig förbränning” tagits fram. Dessa faktorer kan anpassas till nationella förhållanden genom att vägas in i de nationella emissionsfaktorerena.

Emissionsmätningar genomfördes på kaminer och pannor som är representativa och förekommer i bostadshus i de nordiska länderna. Det är stor skillnad på vilka teknologier som är allmänt förekommande i de olika nordiska länderna, men de vanligaste teknologierna ingick i mätprogrammet.

Mätningar gjordes enligt EN-standarder för pannor och kaminer. Några kaminer testades även enligt Norsk standard. Provtagning av $PM_{2.5}$, EC och OC gjordes i spädtunnel och inte i varma rökgaser (d.v.s. i proverna ingår kondenserbara ämnen).

I de nationella inventeringarna saknas oftast detaljerad kunskap om beståndet av teknologier. De teknologier som testades grupperades därför efter likheter i teknologi och emissionsnivå, i syftet att ta fram emissionsfaktorer som är anpassade för tillgängliga aktivitetsdata.

De äldre typerna av teknologier visade generellt högre emissionsnivåer än modernare utrustning. Till exempel mättes emissionsnivåer som var 5–10 gånger högre (beroende på ämne) från en traditionell vedpanna än från moderna ved- eller pelletspannor. Bland kaminerna var skillnaden generellt inte lika stor, med upp till 2 gånger högre emissionsnivåer från äldre teknologier (kakelugn, äldre järnkamin) jämfört med moderna vedkaminer.

Förutom de testförhållanden som föreskrivs i EN-standarder undersöktes även emissionsnivåer vid icke optimala förbränningsförhållanden. Detta gjordes för att

fånga variationer i emissioner som beror på olika sätt att elda. Standardförhållandena, d.v.s. nominell last och bränsle med föreskriven fukthalt (standardbränsle), utökades mätprogrammet och inbegrep även tester med fuktig ved eller vid del-last (för litet bränsleinlägg för att få optimal förbränning). Ett fåtal tester gjordes även med torrare ved eller med för stora vedinlägg.

Förbränning med för lite ved i pannorna (del-last) medförde mellan 2–6 gånger högre emissioner, medan fuktig ved gav emissionsnivåer som var 1.5–2 gånger högre än vid standardförhållanden. De moderna kaminerna var känsliga för fuktig ved, där emissioner av t.ex. $PM_{2.5}$ och OC var i storleksordningen 5–8 gånger högre än då standardbränsle användes. De äldre teknologierna, kakelugn och murad ugn (masonry stove), var å andra sidan knappt påverkade av fuktig ved och nivåerna på emissioner var jämförbara med förbränning med standardbränsle. Den högre inverkan av fuktig ved i moderna kaminer beror troligtvis på begränsad kapacitet i luftsystemen i många moderna kaminer. För kaminerna innebar förbränning med för lite bränsle generellt 1.5–3.5 gånger högre emissioner. Den påtagliga känsligheten för förbränningsförhållanden (fuktig ved, icke optimal bränslemängd) betyder att detta behöver tas hänsyn till i nationella emissionsinventeringar där "verkliga" emissioner ska beräknas. Andelen "dålig förbränning" behöver uppskattas i varje land för att kunna väga in dessa förhållanden i de nationella emissionsfaktorerna.

I testresultaten var det tydligt att emissioner av EC inte korrelerar med emissioner av $PM_{2.5}$, och även att emissioner av EC påverkades i mindre utsträckning av "dålig förbränning" än de flesta andra ämnen som mättes. I litteraturen anges i många fall emissionsfaktorer för EC som en andel av emissionsfaktorn för $PM_{2.5}$. Resultaten från mätningarna visar att detta inte stämmer med verkligheten.

En jämförelse mellan nationella emissionsfaktorer och resultaten från mätningarna visar att det ibland är stora skillnader. Det finns exempel på nationella emissionsfaktorer som är betydligt högre eller betydligt lägre än mätningarnas resultat.

Jämförelsen visar också stora skillander i nuvarande emissionsfaktorer mellen de nordiska länderna. En av anledningarna är att de nationella faktorerna är baserade på resultat från mätningar som gjorts med olika (godkända) mätstandarder (t.ex. i varma rökgaser eller i spädtunnel, enligt EN-standard eller Norsk standard). Om det inte är så att det föreligger verkliga skillnader mellan länderna behöver nivån på emissionsfaktorer harmoniseras för att resultaten från de nationella inventeringarna ska vara jämförbara. Resultaten från de redovisade mätningarna bidrar med kunskap för att kunna utveckla emissionsinventeringar som är mer jämförbara mellan de nordiska länderna.

Mätresultaten och de emissionsfaktorer som tagits fram i detta projekt ökar kunskapsbasen för att minska osäkerheten vid beräkning av emissioner av SLCP (och $PM_{2.5}$) i framtiden. Mätprogrammet visade dock också att det kan vara ganska stor variation när identiska tester upprepas. Det innebär att fler, väl designade, mätningar skulle bidra med ytterligare information som kan användas för att förbättra emissionsfaktorerna så att de reflekterar verkligheten med ännu högre säkerhet.

Annex

Factors affecting combustion conditions

Operation and maintenance of equipment

Even an advanced equipment can be operated in a way to release high emissions. In general, modern equipment is easier to operate due to better air systems, firebox insulation and easier valve control. In addition, modern stoves/boilers have various degrees of automation onboard, which enables them to adapt to and to control the combustion parameters depending on the conditions of the combustion at any time.

The equipment should always be used according to the specific instructions. This ensures efficient and optimised combustion conditions. Efficient combustion decreases emissions and also keeps the equipment cleaner as less soot is generated on the surfaces of the combustion chamber and channels. Ash in the combustion chamber impacts the air circulation of combustion air and flue gases and increases particle emissions. When the combustion efficiency is low, the heat content of the fuel is not fully utilized causing higher emissions per energy unit and thus also extra fuel costs.

To maintain an even efficiency, regular sweeping of the surfaces is needed. In some modern pellet boilers, automatic sweeping is arranged in the convection space of the boiler. In stoves and fire places, regular removal of ashes from the grate is necessary to ensure air flow from below and to minimize particle emissions. Chimney sweeping should in all cases be carried out regularly.

Over time the equipment may be worn and in need of repair in order to maintain efficient combustion conditions. In some types of stoves gaskets and firebox insulation material deteriorate over time and have to be replaced regularly (depending on the intensity of the use of the stove). Broken or missing firebox insulation bricks leads to colder combustion, which in turn lead to higher emissions. For boilers where air supply is optimized through automatization, for example a leaking door will allow plenty of air to unintentionally enter into the firebox and counteract the control of the combustion with the valve system.

Fuel quality

The fuel log size, its density, moisture and chemical properties[4] impact emissions. To maximize the energy output from wood and to minimize emission levels, only dry and clean wood should be combusted, and not contaminated wood or waste.

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[4] Ash content and composition.

The moisture content of wood has been identified as the most important factor related to the efficiency of burning, i.e. production of heat. For optimal conditions the wood fuel moisture should be within a range of typically 12–20%. Firewood having higher moisture content is hard to ignite. As long as the wood is moist some of the produced heat during combustion is used to evaporate the moisture and the pyrolysis will not be strong enough to enable the temperature to rise sufficiently high to ensure complete combustion and thus some non-carbonized wood remains. An increase of moisture content of wood from 9% to 25% decreases the efficiency of burning by 7% (Pietilä, 2005). The measured particle emissions when burning moist wood compared to dry wood are 2–3 fold (Tissari et al., 2005, UEF, and current measurement campaign).

Results of the current measurement campaign show strong indications that old stoves that have a higher capacity in the air system are better able of burning moist firewood than modern stoves with limited capacity. Both the amount of air and the ability to supply plenty of primary air seems beneficial to burning moist firewood. According to UEF (2005) if moist wood is combusted, it should be combusted during the last batch.

It was also noted in the current measurement campaign that moderately over-dried firewood (8–12%) does not have any significant adverse influence on the emissions. It is generally recognized that extremely dry firewood (0–5%), e.g. waste wood from industrial manufacture of windows or floors, is too dry to burn properly and is likely to cause excessive emissions of soot (Carlsson et al., 2016).

The user can influence the moisture content of wood by ensuring suitable storage conditions for long enough time before use. Storage facilities outdoors should be protected from rain and excess moisture, allowing for air circulation in the wood pile. When freshly cut the moisture content of wood is around 50% which should be decreased to below 20% before combustion. Wood should be taken indoors some days before it is used to decrease moisture and to adjust the temperature of the wood. (VALVIRA, 2008)

User influence during firing

Ignition

Manually fed wood boilers are best ignited using a small amount of small size dry logs, while creating good draught (to quickly raise the temperature) by opening the bypass damper and keeping the lid partly open until the fire has properly lit up (Rakentaja, 2016).

In stoves, ovens and fireplaces ignition from the top has been identified to create 15% less emissions than ignition from the bottom (UEF).

Fuel batch sizes and quantity of fuel

Modern stoves are optimized for moderate to low heat generation. Typically, a modern stove is tested to 5 kW nominal heat output, corresponding to a burn rate of approximately 1 kg firewood per hour. In modern, well insulated dwellings this is sufficient to maintain comfort temperature. In the modern stove the capacity of the air system is downsized compared to older technologies. At the NS3058 particle test, earlier most stoves were able to enter the higher burn rates 3 (>1,9 kg firewood/h) and 4 (> 2,8 kg/h). Nowadays, in modern stoves, it is quite common that the uppermost burn rate attainable is burn rate 2 (>1,25 kg/h).

The optimal batch size depends on the appliance used. As a rule-of-thumb, 1 kg of wood per 100 kg of equipment mass can be burned in a heat storing stove. For instance, for masonry stoves, typical fuel loads are 10 kg wood/1000 kg of stove mass (UEF 2005, VALVIRA 2008). Overloading a stove leads to shortage of combustion air, which in turn leads to higher emissions.

Small batch sizes seem to lead to lower efficiency due to non-optimal air supply. The small combustion area does not cover the grate completely and therefore primary air flow passes the batch without reaction and cools the batch. Also, high carbon monoxide levels have been measured while carbon dioxide levels are low (Pietilä 2005).

Wood log size

The optimal log size of the wood depends on the appliance used, however, smaller log size generally leads to lower emissions. The optimal diameter of wood logs has been identified to be around 10 cm.

Compared to larger log size (> 50 cm length), combustion of small size wood logs contributes to more complete combustion in higher temperature, giving shorter burning times. The greater surface area of small logs increases heat transfer velocity and thus leads to increased pyrolysis. Small log size is also beneficial when burning moist wood because it promotes strong enough combustion for complete burning of the logs.

Using smaller batches and larger log sizes tends to lead to unburnt wood remaining in case other factors affecting the combustion are not optimized to meet those conditions.

Arrangement of logs in manually fed appliances

The gasification of wood can be optimized using compact or loose arrangement of logs in the combustion chamber. Compact arrangement decreases the velocity of gasification while a loose setting increases the velocity. During the last batch in a burn cycle, there may be a need to restrict gasification by closing the air inlet and by using a compact arrangement and larger log sizes. The leading principle is that the wood logs should not be placed tightly against the wall, which will prevent air circulation. Upright arrangements of wood logs has been identified to decrease emissions by approximately 10% compared to horizontal arrangement in most stoves (UEF 2005).

Optimizing the air supply

The combustion process is not steady and conditions vary largely during the different phases of a burn cycle. Optimal air demand in wood combustion appliances varies depending on the appliance technology, the stage of combustion and the quality and quantity of the fuel. A feed of secondary air helps to control carbon monoxide and gas phase hydrocarbons. Optimization of the air supply can be done automatically, through in-built constructions, or by the user.

Automatic optimization of air supply can be mechanisms that measure e.g. carbon monoxide or carbon dioxide concentrations and temperature throughout the combustion process, and optimize the air flow to ensure conditions as favorable as possible for complete combustion.

Inbuilt constructions in the combustion equipment are used to improve the air feed and to optimize draught. Natural draught is impacted by the pressure difference of the combustion chamber and the chimney, therefore the height of the chimney needs to be optimized for the building and the combustion equipment (Jokiniemi et al., 2008). At tests carried out as part of a Finnish project (Jokiniemi et al., 2008) the measurements were made at a fixed (low) flue draft of -12 Pa to mimic worst case draught conditions. Most chimneys build up higher flue draft, 20 Pa or more, if only the chimney is 3–4 m high.

Leaks in the system (e.g. at the entry of the connecting fluepipe into the chimney) may arise due to installation errors. In such a case fluedraft is impacted, leading to potentially reduced combustion quality.

The colour of the flue gas indicates if the natural draught is sufficient, where light or transparent flue gas contains only evaporated moisture and hydrocarbons. In case of bad draught or too moist wood the colour is dark grey or black and contains unburnt material.

The combination of moist firewood and a non-optimal-height (too low) chimney increases emissions. If instead the draught of the chimney is improved, this increases air supply which is beneficial for combustion of moist wood.

In case the flue draft is too high the burn rate is often accelerated towards higher heat output. If excessively high flue draft is a permanent problem, it can be dealt with by installing a flue draft regulator in the chimney. Conversely, if the flue draft is generally too low, it can be dealt with by installing an flue gas fan on top of the chimney.

The user can manually (a) improve combustion conditions by increasing or decreasing the air flow to the combustion chamber and (b) improve draught by adjusting the ventilation in the room by e.g. turning room ventilation device into "fireplace mode", when such a mode is available, shutting off kitchen hoods and opening windows in the room where the combustion appliance is.

Smoldering combustion above all occurs if the air valve is throttled while there is still unburnt firewood. This might happen if the user attempts to control heat output by throttling the valve rather than reducing the fuel load.

The amber phase air supply arrangements have the second largest impact on combustion efficiency after wood moisture content (Pietilä, 2005). The amber remaining towards the end of a firing cycle burns slowly. In the amber the combustion reaction occurs in the solid coal and not between gaseous components as in the earlier combustion phases. The amber phase should be minimized to minimize heat losses through the chimney. Secondary air inlets and the lid can be closed, to allow only the flow of primary air. When the amber is almost finished, air flow to the chimney can be closed, however, the remaining amber may not include any unburnt wood in order to avoid incomplete combustion.

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EMISSION FACTORS FOR SLCP EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION IN THE NORDIC COUNTRIES

Emission inventories of Short Lived Climate Pollutants (SLCP), and especially of Black Carbon are uncertain and not always comparable between countries. Comparable and reliable emission inventories are essential when aiming for efficient strategies and policies for reduced emissions.

The overall objective of this project is to improve the Nordic emission inventories of SLCPs. This report presents the results from the second phase of the project, emission measurements of SLCP and particulate matter from residential wood combustion. Measurements were done on residential biomass combustion appliances representative for the Nordic countries, covering elemental carbon (EC), organic carbon (OC), particulate matter (PM2.5), methane (CH4) and non-methane volatile organic compounds (NMVOC). Emission factors were developed for standard combustion conditions, as well as for poor combustion conditions.

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